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BOARD OF WATER SUPPLY

GEOLOGY AND GROUND-WATER RESOURCES

OF THE

MOANALUA-HALAWA DISTRICT

by

Chester K. Wentworth

Board of Water Supply

Honolulu, Hawaii

1942

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INTRODUCTION

Location and extent

The present report covers the Moanalua district as referred to in previous reports of this series, which is the whole of the Honolulu district northwest of the northwestern boundary of Kalihi Valley, together with the Halawa Valley drainage basin and adjacent parts of the Pearl Harbor coastal plain. It, therefore, includes a part of the Honolulu district and a part of the Ewa district of Oahu. Similarly, there are included parts of the Honolulu and Pearl Harbor artesian areas, as commonly understood in Hawaii. The interrelationship between these areas will be discussed in greater detail elsewhere in this report. (Figure 1)

The island of Oahu consists chiefly of two volcanic domes, the eastern or Koolau dome and the western or Waianae dome. Each of these domes was originally somewhat elongated and by erosion has become more so. In their present eroded condition, each with a somewhat sharp crest a number of miles in length, they are commonly referred to as the Koolau and Waianae Ranges. Each range is more eroded on the side toward the ocean and less so on the side that faces the saddle or plateau which lies between them. The Koolau dome was built later, after the Waianae dome was completed, so that the greater part of this saddle is composed of the later Koolau lava flows flooded against and wrapped around the already dissected eastern flanks of the Waianae Range.

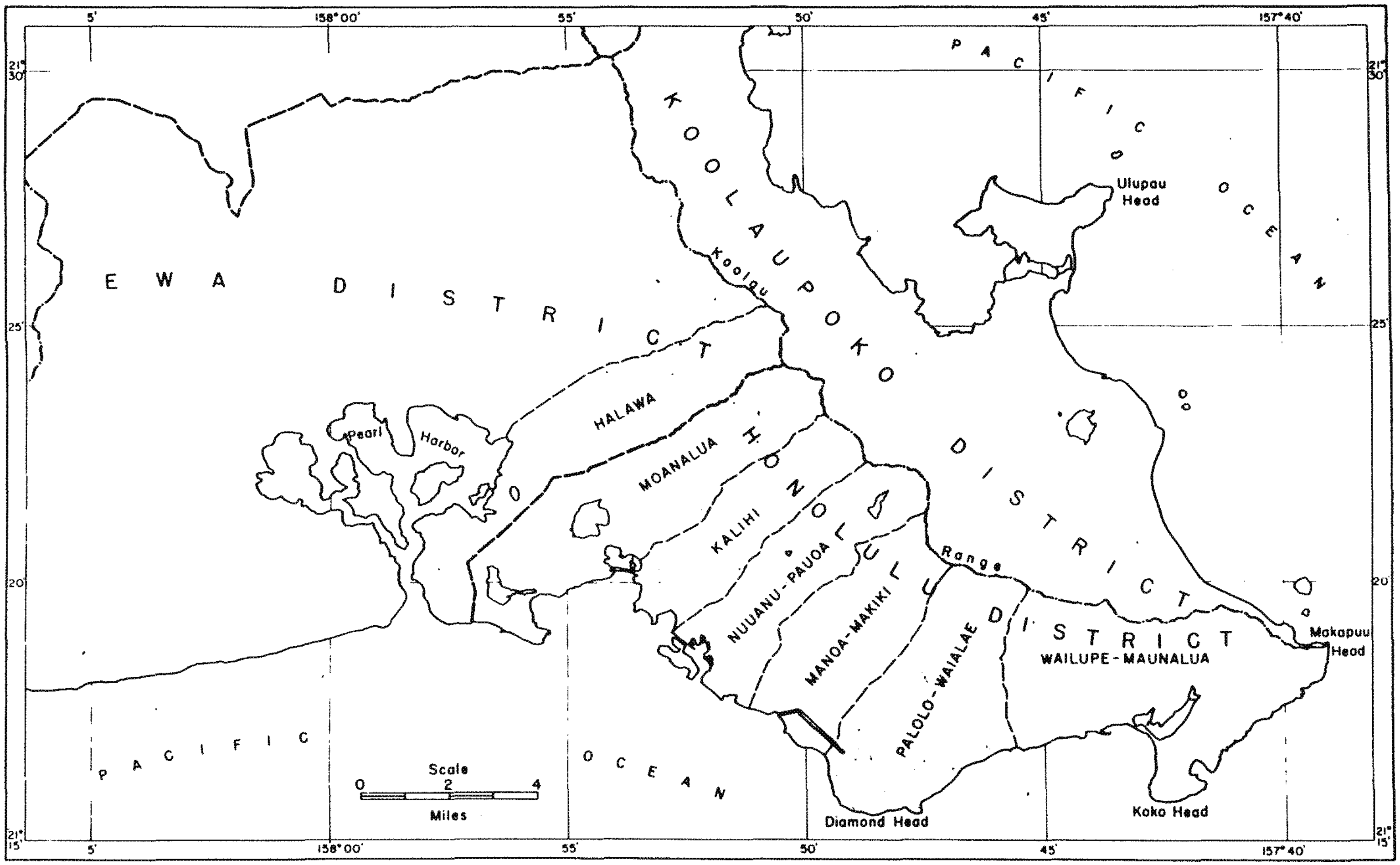

Figure 1 - Outline map showing geologic survey districts of the Honolulu watershed and adjacent areas. The geologic survey has been completed for the area shown in blue.

The Koolau Range is longer than the Waianae Range, and its southeastern end extends nearly 20 miles farther southeast. The leeward slope of this part faces the ocean and carries at its foot a coastal plain, which east of Diamond Head is narrow and discontinuous, but which becomes wider in the part occupied by much of the city of Honolulu and still wider in the part that swings westward to include Pearl Harbor and flank the southern end of the Waianae Range. (See Figure 2)

In addition to the leeward valleys of the southeastern third of the Koolau Range, which drain almost directly to the sea, the leeward valleys of nearly another third of the range are diverted southward from the divide of the Schofield Plateau to discharge into the western arms of Pearl Harbor, and unquestionably this concentration of discharge from an eroding area has aided in the building of the wide coastal plain of this Pearl Harbor sector.

By combining the Moanalua and Halawa districts in this report, opportunity is afforded for a transition from the Honolulu to the Pearl Harbor area, with a discussion of similarities and differences at several points. This report therefore completes description of the geology and ground-water resources of the Honolulu district and commences that of the Pearl Harbor area of the Ewa district.

The Moanalua-Halawa district as covered herein includes the leeward slope of the Koolau Range, consisting of the valleys of Kahauiki, Manaiki, Moanalua, South Halawa, North Halawa and Aiea, together with the adjacent coastal plain and crater area from the Kalihi Channel to Pearl Harbor, an area three to five miles wide and

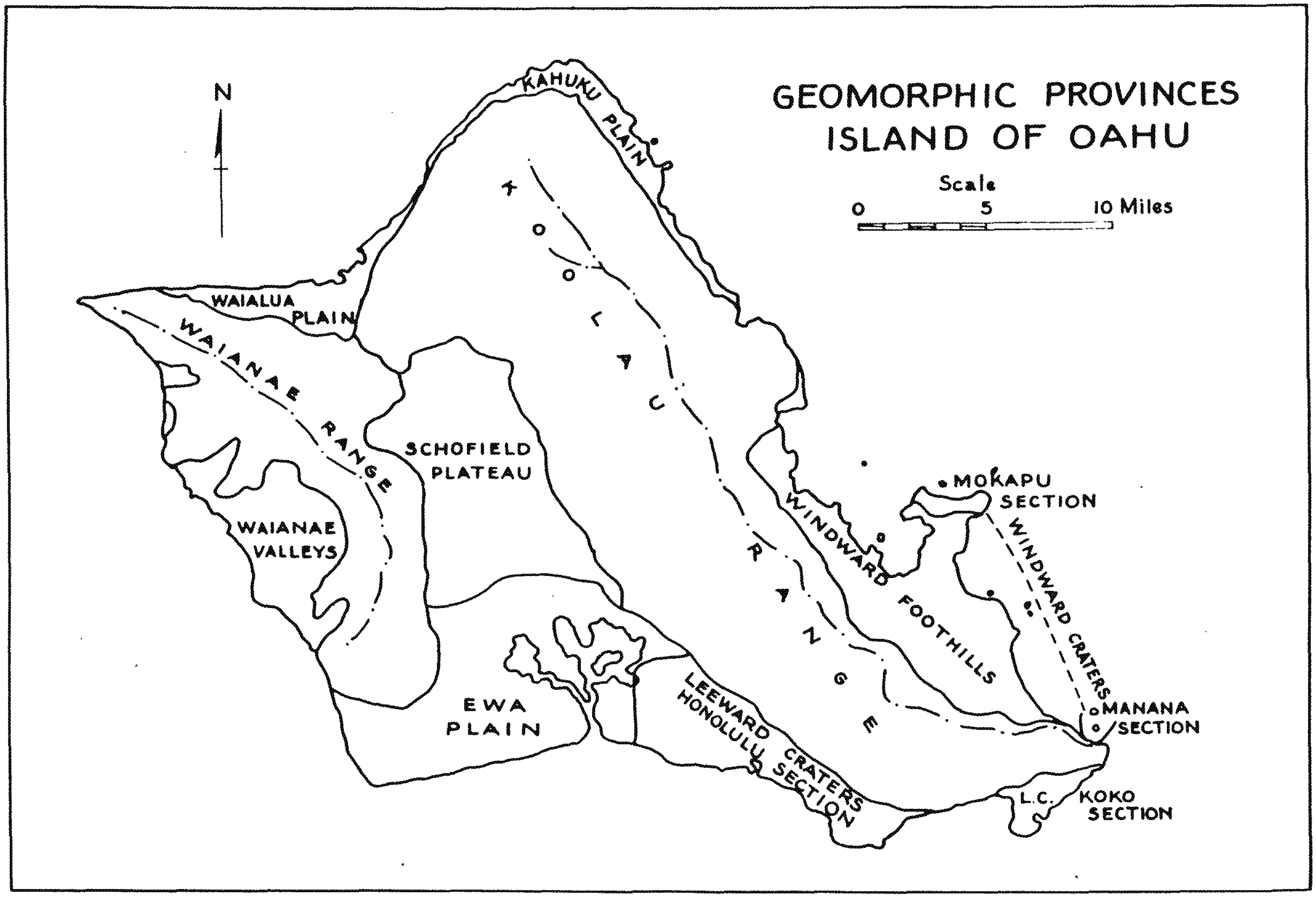

Figure 2 - Index map showing chief geomorphic provinces of the Island of Oahu. Included in each province is an area in which a similar general type of topography is found and in which a somewhat uniform development of land forms has prevailed during geologic time.

about ten miles in length from the range crest to the coast. (Figure 3) Commencing at a point on the Kalihi Channel shore near Mokumoa Island, the boundary of this district passes inland along the northwestern divide of Kalihi Valley past the head of Kahauiki Valley to the crest of the range at Puu Kahuauli, at 2700 feet, thence northward and westward along the crest, past the heads of Manaiki, Moanalua, South Halawa and North Halawa Valleys, to the eastern corner of the head of Kalauao Valley, thence generally southwestward along the southeastern divide of Kalauao Valley, and along the northwestern margins of the ahupuaas of Halawa and Aiea, to the shore of Pearl Harbor at Aiea Bay, thence along the eastern shore of Pearl Harbor past Watertown and Ahua Point to the point of beginning. (Figures 1 and 5) The total area is as follows: Moanalua portion 15.84 square miles, Halawa portion 15.54 square miles; both 31.38 square miles.

Inter-relation between Honolulu and Pearl Harbor areas

The Honolulu artesian area, as is now well known, is divided into several so-called isopiestic areas, each of which is marked by nearly identical artesian heads in all the wells within its boundaries. The several isopiestic areas are separated in their hydraulic behavior by relatively impervious barriers formed of sub-sealevel sedimentary fill in the bottoms of the chief valleys. The central Beretania or No. 2 area of Honolulu has the highest artesian heads, with progressive lowering of heads in the areas eastward and westward.

Figure 3 - Panoramic view southeast, east, northeast and north from rim of Salt Lake Crater. On the horizon, starting at the right, are Diamond Head, Punchbowl. Roundtop, Sugarloaf, and Tantalus. The principal bit of the Koolau crest shown is the eastern part of the head rim of Moanalua Valley. At the left commencing with near foreground, are slope of Salt Crater, lower Moanalua Gorge, Moanalua-Manaiki flow slope facet, and at distance the inner Red Hill spur and crest of the range. Negatives No. 21271-2-3-4.

The Pearl Harbor artesian area has been considered to be one unit, No. 6, (1) with its eastern boundary fixed by the sedimentary

(1) Stearns, H. T., Geology and Ground-Water Resources of the Island of Oahu, Hawaii, Territory of Hawaii, Division of Hydrography, Bulletin 1, pp. 257-267, 1935.

fill in Halawa Valley bottom. The levels of wells in the Pearl Harbor area, however, show much more systematic variation from place to place than do wells in any one of the typical units of the Honolulu area. Furthermore, as will be brought out later, the position of the boundary between areas 4 and 6 at Halawa Valley is not so clearly indicated by known hydrologic or geologic facts as some of the other boundaries.

The writer's original plan was to complete the Moanalua report and thus finish the areal investigation of the geology and ground-water resources of the Honolulu watershed. With the augmented rate, however, in increase of draft and recognition of need for additional basal water supplies, attention has been directed toward the Pearl Harbor area. At the same time, a program for the development of basal water by the U. S. Navy in the Red Hill spur became a factor to be reckoned with. Plans were therefore eventually formulated by this office for the construction of the North Halawa Basal Shaft, with a transmission pipe line passing by tunnel through the Red Hill spur, and with an underground emergency connection with the Navy water main in Red Hill. Still further, the Honolulu Plantation Company at Aiea late in 1941, commenced the digging of a vertical shaft to develop basal water at a point about a half mile northeast of Aiea Post Office.

There has thus developed a direct interest in the Pearl Harbor area by the Board of Water Supply, as well as an increasingly complex inter-relationship between shafts and wells and the natural basal supply throughout the whole area from Kalihi Valley to Aiea. Under such conditions, a report on the Moanalua area alone would not only appear academic but would either suffer by lack of adequate consideration of much factual data for the Halawa area or would so overlap the Halawa area that it would seriously duplicate a separate report on the Halawa area. The need for a combined treatment is obvious. Accordingly, the bulk of the present report will present conclusions for the combined area, though certain descriptive sections will deal separately with the Moanalua and Halawa parts.

Purpose, scope and methods of study

Methods used in this study are those described in earlier reports. Each valley, because of the arrangement and length of existing trails and roads, poses its own peculiar problems. For example, in Moanalua Valley, with a good valley-bottom trail nearly to its head and about two miles of automobile road, the head of the valley at the crest of the range is more readily reached by this route than by either of the ridge trails, but the reverse is true of Halawa Valley. Fortunately, there are excellent trails on the ridges north and south of North Halawa Valley which were constructed by the C.C.C. several years ago. Manaiki Valley head is most accessible by climbing the west wall of Kalihi Valley from the military road which traverses Kalihi Valley nearly to its head. After reaching the head of Manaiki, the traverse of its thalweg from 2500 feet to a highway at the rear of Moanalua Gardens, proved to be one of the most time-consuming yet undertaken, owing chiefly to the length and youthful topographic development of the valley.

History and acknowledgements

An outline of previous studies of the Koolau Range has been presented in an earlier report of this series and in a report prepared by the writer and Horace Winchell (1).

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(1) Wentworth, C. K., Palolo-Waialae Report, pp. 6-14, 1938.

Wentworth, C. K., and Winchell, Horace, The Koolau Basalt Series (Manuscript in course of preparation) 1942.

When the writer commenced geologic study of the Honolulu watershed in 1934, attention was first given to Nuuanu Valley, and following that a considerable amount of field work was done in Kalihi and Moanalua, chiefly at lower elevations, as well as in the Waialae area in connection with the planning and construction of the Kalihi and Waialae Underground Pumping Stations. This was followed by work in Manoa Valley in connection with the Manoa Water Suit. In 1937, the geologic work was concentrated on the Palolo-Waialae area and followed by a systematic completing of reports on the Palolo-Waialae, Manoa-Makiki, Kalihi, and Nuuanu-Pauoa Reports in that order.

The present report is based on field work done during late 1941 and 1942, as well as the earlier work of 1934 and 1935. In 1941, the writer was assisted for short periods in the field by Wah Kau Kong and by Anton Postl, both trained primarily in chemistry and each in turn finding more profitable employment in that field elsewhere. Since November, Masami Iwamura has served very effectively as field assistant. Rijo Hori has continued his generally satisfactory work as laboratory assistant and draftsman.

The outbreak of the war on December 7, came practically at the beginning of field work on the major part of the area dealt with in this report. Naturally, with greatly increased military activity and the establishment of martial law in the Territory, certain restrictions have been encountered in connection with the geologic work, especially since this area includes or is adjacent to several large military posts. Notwithstanding this condition, with increased need for requesting passes and for caution in approaching military positions, no real impediment has been put in the way of the geologic survey, and officers and men of the military service have without exception been courteous and helpful in making any necessary special arrangements.

GEOGRAPHY

Geomorphic divisions

The Moanalua-Halawa district consists of all the leeward slope of the Koolau Range contained between Kalihi and Kalauoa Valleys together with adjacent parts of the coastal plain from Kalihi Entrance to the entrance to Pearl Harbor. As shown in Figure 2, this district includes parts of the Koolau Range geomorphic province, and the

Leeward Crater (Honolulu Section) and Ewa Plain provinces. The relationship of these provinces to the geomorphic subdivision of the whole island of Oahu will be seen by reference to the tabulation below and to Figure 2. Geomorphic provinces are land areas in which masses of rock formed by similar geologic processes have been modified by a unit combination of land sculpturing processes and have reached a somewhat uniform degree of modification by these processes.

Geomorphic Divisions of Oahu

Mountains		
1	Waianae Range	
2	Koolau Range	
Plateaus and Highlands		
3	Schofield Plateau	
4	Windward Highlands	
Mixed Lowlands		
5	Waianae Valleys	
6	Leeward Craters	(Honolulu Section)
7	" "	(Koko Section)
8	Windward Craters	(Mokapu Section)
9	" "	(Manana Section)
Coastal Plains		
10	Ewa Plain	
11	Waialua Plain	
12	Kahuku Plain	

In the Koolau Range province, a dome composed of thin basaltic lava flows has been maturely dissected by streams cutting radial valleys whose rock bottoms reach in some cases 1000 feet below present sea level and whose head branches have destroyed 100 percent of the original surface of the dome. In the lower slopes, however, of some sectors, as much as 10 to 20 percent of the area of the original dome in this belt has been approximately preserved in the so-called flow-slope facets, typically represented by Wilhelmina Rise, St. Louis Heights, etc., back of the Honolulu coastal plain. (See Figure 3)

The Leeward Craters province is an area marginal to the leeward periphery of the dome above sea level in which the formation of a fairly wide coastal plain and of the cap rock sediments which compose it have been aided and conditioned by the prior building of secondary tuff craters in peripheral or offshore positions and by the growth of coral reefs at various sea levels marginal to these craters. This area extends westward to include the various craters of the Salt Lake group.

West of the Salt Lake craters, a still wider part of the coastal plain called the Ewa Plain province lies south of the Schofield Plateau or saddle and extends westward to flank the southern end of the Waianae Range. This area, including the part under the shallow waters of Pearl Harbor, is a filled embayment between the two ranges, and owes its origin to its leeward position and to the large amount of land-derived detritus which has in past time been brought in by streams These streams converge here from the heavily-watered central part of the leeward slope of the Koolau dome. Coral reefs have veneered this area at various levels and played also an important part in the growth of the plain.

Topography and drainage

GENERAL

The main outlines of the Koolau dome have been described in earlier reports (1). The Moanalua-Halawa district is situated on the leeward slope at the junction between parts having direct drainage to the sea and those having only drainage to Pearl Harbor. This distinction is accentuated by the mass of the Salt Lake craters which stands between the Kalihi entrance, into which Kalihi and Moanalua Streams drain, and Pearl Harbor, which gathers the drainage of several of the longest streams west of Moanalua. The line between the Honolulu district and the Ewa district, each one of the six major political and legal districts of Oahu, passes between Moanalua and Halawa Valleys and across the Salt Lake crater area. Apparently, this natural line of subdivision between direct drainage and Pearl Harbor drainage was practically recognized by the Hawaiians at a very early date, certainly several hundred years ago (2).

(1) Nuuanu-Pauoa Report, 1941, pp. 6-7.

(2) King, R. D., Districts in the Hawaiian Islands, (In Coulters Gazetteer of the Territory of Hawaii) University of Hawaii, Research Publication No. 11, pp. 214-224, 1935.

In the mountainous section, from the ends of the intervalley spurs to the present crest of the range, there is no marked topographic break or contrast between the leeward slope in the Honolulu district and that in the Ewa district to the west. However, as these studies have proceeded, attention has been drawn recurrently to the fact that a number of valleys in the Honolulu area have rock bottoms cut several hundred feet below present sea level at the ends of the spur (Palolo, Manoa, Nuuanu, Kalihi) and that none of the valleys west of Red Hill has a known rock bottom depth to more than possibly 100 to 200 feet below sea level, nor width between walls which would accommodate such depth. The same is true of the valleys of the Honolulu district east of Palolo. Thus the deep valleys, all variously refilled to broad bottoms somewhat above present sea level, seem to be confined to the sector from Diamond Head to Red Hill. This fact suggests the possibility that this section of the Koolau Range may have had a longer history than the remainder of the range, raising a question which will be discussed elsewhere.

The Moanalua-Halawa district, while straddling the boundary between the Honolulu and Ewa districts, heads at the crest of the Koolau Range at a point nearly midway of the whole length of the Koolaupoko district. Except for the occurrence of the striking cirque-like head of Haiku Valley at this point, no significant change or demarcation of the Koolaupoko district is located here.

The crest of the range at the head of the district covered in this report has several culminating summit peaks with elevations between 2700 and 2850 feet. Its lowest saddle is at the head of Moanalua Valley, at slightly over 1700 feet. Except for this depression, none of the saddles of this part of the range is lower than 2250 feet, or more than 200 feet below adjacent parts of the range crest. (Figure 4)

Figure 4 - Panoramic view from Moanalua-Manaiki divide inland from 1520 foot peak. At right is head portion of Manaiki Valley with peak of Lanihuli showing beyond the Manaiki-Kalihi divide. At left is considerable portion of the head of Moanalua Valley with range crest and radial ridge crests to the northwest. The contrast in topographic development between Moanalua and Manaiki Valleys is well shown. Negatives No. 21287-88-89-90.

THE KAHAUIKI-MANAIKI AREA

Moanalua Valley and the two Halawa Valleys form rather broad, distinct subprovinces which adjoin each other along the line of narrow boundary ridges. Between Moanalua and Kalihi Valleys is an area, broad at the margin of the range and narrow at the crest, which is occupied by the narrow, through valley of Manaiki and by the shorter valleys of Kahauiki and others cut in the triangular flow-slope facet which lies inland from Fort Shafter. This area, including Manaiki Valley is treated in the following paragraphs. (Figure 5) The seaward margin of this province, where the ends of Koolau spurs pass from view, is flanked by remnants of the Fort Shafter terrace, which will be discussed in detail below. The seaward end of the Kahauiki-Manaiki area is about two miles wide, the lower end of Manaiki Valley itself having a width of only about 1/3 mile. Manaiki Valley has a width ranging from 1500 to 3000 feet, with a length of five miles from the crest of the range to the inner margin of the coastal plain in Moanalua Gardens. It has only one or two tributaries other than the numerous chutes which drain its steep side walls, and in this respect its nearest counterparts in the Honolulu area are such valleys as Waialaenui or Kapakahi. A long section of the middle course of Manaiki Valley is characterized by a channel winding from side to side of the valley, in a belt not over 500 feet wide. The outer banks are cut against the rock wall, and into each bend extends a sloping spur covered by talus and alluvium but underlain by bedrock. (Figure 6) Though this pattern resembles entrenched meanders, it is not clear that such a course has been assumed on a graded valley bottom, a problem which from the geomorphic standpoint merits further study and

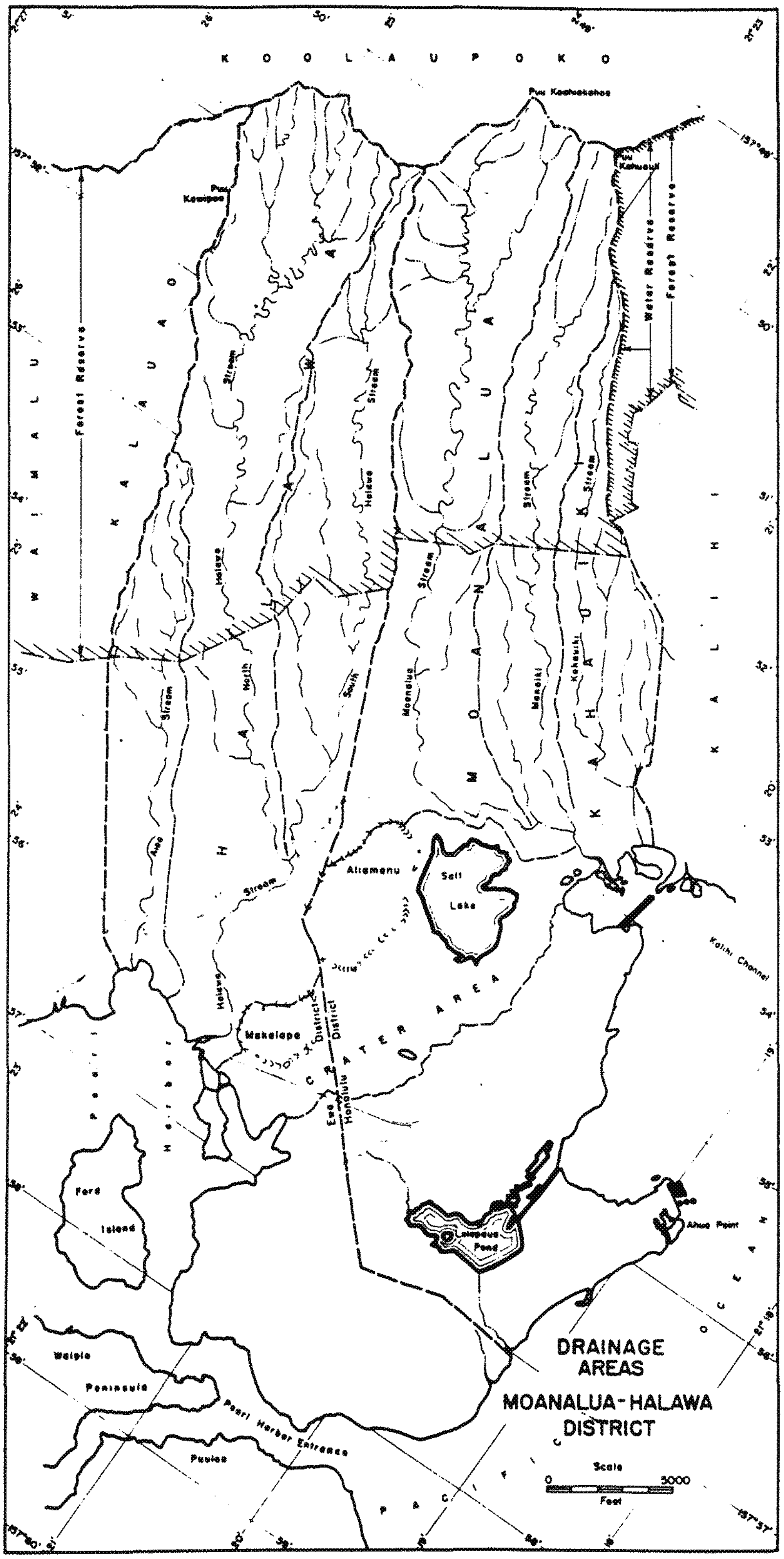

Figure 5 - Map showing component drainage areas of the Moanalua-Halawa district and the position of the Forest Reserve line.

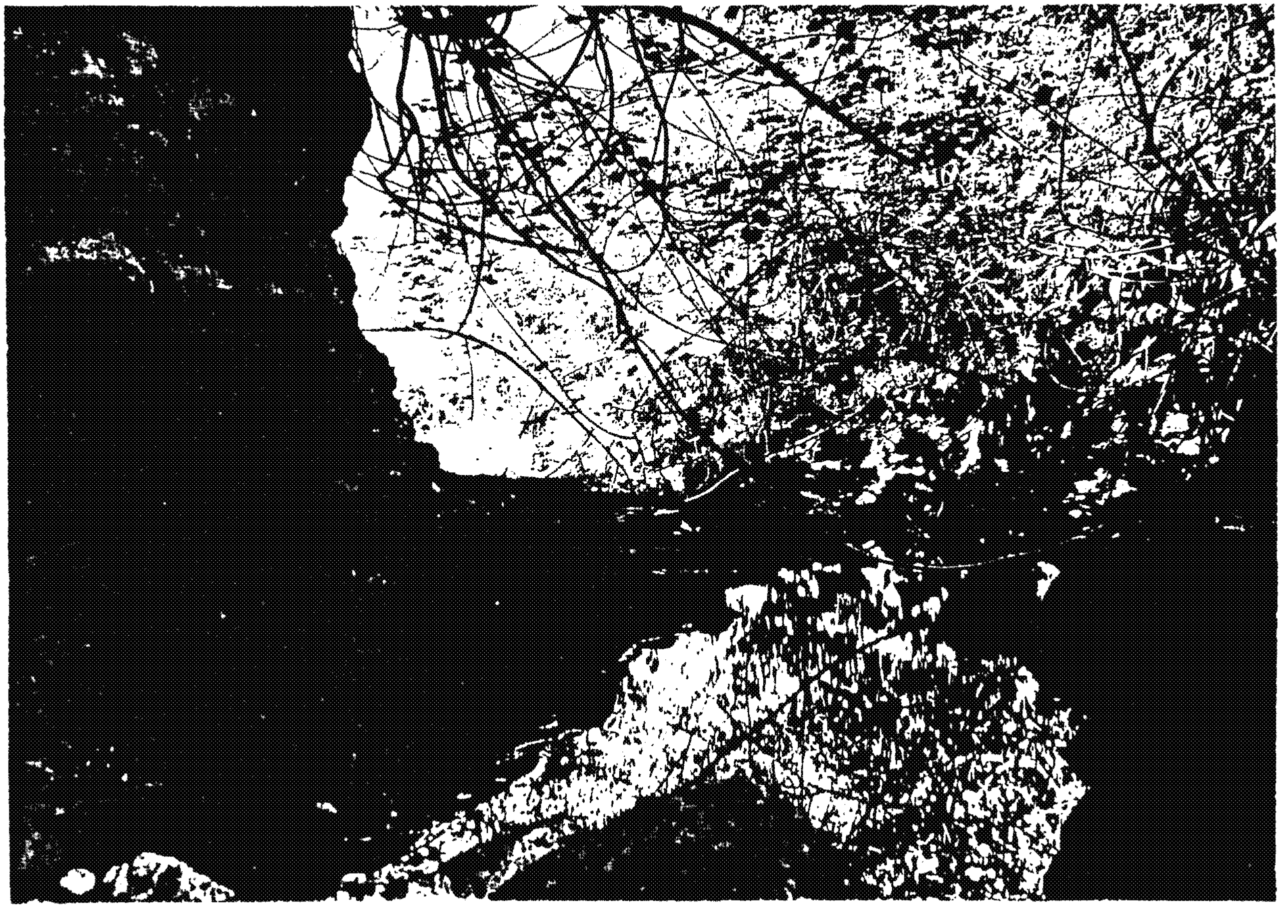

Figure 6 - View looking down Manaiki channel at a point where Koolau rock, in place, extends continuously across the channel and up each bank. Negative No. 21292.

discussion. Only about a mile of the lower valley has a significant width of valley flat, in which the stream is less deeply cut. The inland part of the valley is marked by a somewhat steeper channel with less pronounced meanders, but the contrast between this part and the middle section is less marked than in most of the larger valleys.

The side walls of Manaiki are mostly marked by the alternating chutes and ribs of similar slope, and only in a few places is there any appreciable break where a larger tributary enters. The greatest depth of about 800 feet occurs around two miles inland from Moanalua Gardens, and the prevailing depth through much of the length is 500 feet. The head of Manaiki borders on Kalihi Valley for about 1 mile inland from the narrow head of Kahauiki Valley. Contrast in the grades of Manaiki and Kalihi Valleys is shown by the fact that the distance of the 1000-foot contour from the crest of the Koolau Range in Kalihi Valley is 1000 feet and in Manaiki Valley, almost two miles. The head profile of Manaiki is a very slight sag in the crest of the range, but that of Kalihi is a broad, parabolic curve, cut down to about 1400 feet, which has been described in an earlier report (1).

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(1) Kalihi Report, p. 12, figure 9, 1941.

Kahauiki Valley, while not a through valley in the sense of reaching the crest of the range, is nevertheless a true mountain valley as distinguished from those cut only as shallow troughs on the surface of flow-slope facets. This valley is graded to the level of the Fort Shafter terrace and occupies a strip 1000 to 1500 feet wide along the western edge of the triangular flow-slope facet. It reaches a maximum depth of about 600 feet, and its channel shows a less meandered course than Manaiki. The divide between it and Manaiki is everywhere a narrow-crested ridge. The head of the valley reaches the elevation of 1650 feet against the Kalihi divide.

The apex of the Kahauiki flow-slope facet proper is a peak of 1330-foot elevation about two miles inland from the margin of the Fort Shafter terrace. On this facet are four small valleys, one of which passes down over the northwest wall of Kalihi Valley, and the other three emerge onto the Fort Shafter terrace, where they all eventually join Kahauiki. Maximum depths of these valleys only locally reach 100 to 200 feet.

MOANALUA VALLEY

The mountain portion of Moanalua is 0.8 to 1.5 miles wide and a little over 5 miles long. On the southeast side is a small flow-slope facet culminating at an apex at 1270 feet. (Figure 3) On this facet are several shallow valleys, one each draining to the Moanalua and Manaiki sides, and some going down the seaward margin of the facet which faces the lower Moanalua Gorge. Northwest of this facet, the lower part of Moanalua Valley for nearly two miles inland has a valley flat several hundred to 1000 feet wide and on the northern side is a remnant of terrace built partly of gravel and partly of Salt Lake tuff which is akin to the Fort Shafter terrace and to the corresponding terraces in Halawa Valley. There is only a small narrow flow-slope facet on the Red Hill spur with an apex at about 800 feet and about $1\frac{1}{4}$ miles inland from the Red Hill saddle between the Red Hill spur and the in-facing slope of Aliamanu Crater. (Figure 7)

Figure 7 - View down lower Moanalua Valley from a point about $1\frac{1}{2}$ miles inland from the Red Hill saddle. Of two light areas near center, that to left is valley flat of present stream, that to ~~left~~ is remnant of Fort Shafter terrace. Aliamanu Crater is beyond (center), and Salt Lake beyond and to the left. Negative No. 21242.

The inland section of Moanalua Valley for about two miles is characterized by a meandering channel course, alternately swinging across a belt 400 to 800 feet wide. (Figure 4) The lower ends of the spurs, each extending into a meander loop, have fairly low slopes, but the surface is by no means a valley flat. At the inner end of this stretch is the junction of two chief branches, the northernmost one of which heads at a 1700-foot saddle overlooking the southeast margin of the head of Haiku Valley, and the southern one draining a rugged mountain area which culminates in the 2800-foot crest overlooking Luluku Valley. Beside the two head tributaries, there are two other tributaries that come from behind sliver ridges which join Moanalua Stream from opposite sides at about two miles inland from the margin of the range. The topography of the walls throughout most of the length of Moanalua is rugged and steep, with a more mature development of side chutes and valleys than Manaiki Valley, but less so than Kalihi or Nuuanu Valleys. (Figure 8)

HALAWA VALLEYS

The courses of the two distinct mountain streams, North Halawa and South Halawa, are joined a short distance toward Pearl Harbor from the main highway, and the combined channel extends about two miles to its mouth. The two streams through most of their course are nearly equal in size, and but for the accident of their joining on the coastal plain probably due to diversion when the Salt Lake craters were formed, would be considered separate streams. South Halawa Valley parallels the Red Hill ridge and is mostly 3/4 mile to 1 mile wide, and slightly over 5 miles long. (Figure 9) Toward the crest

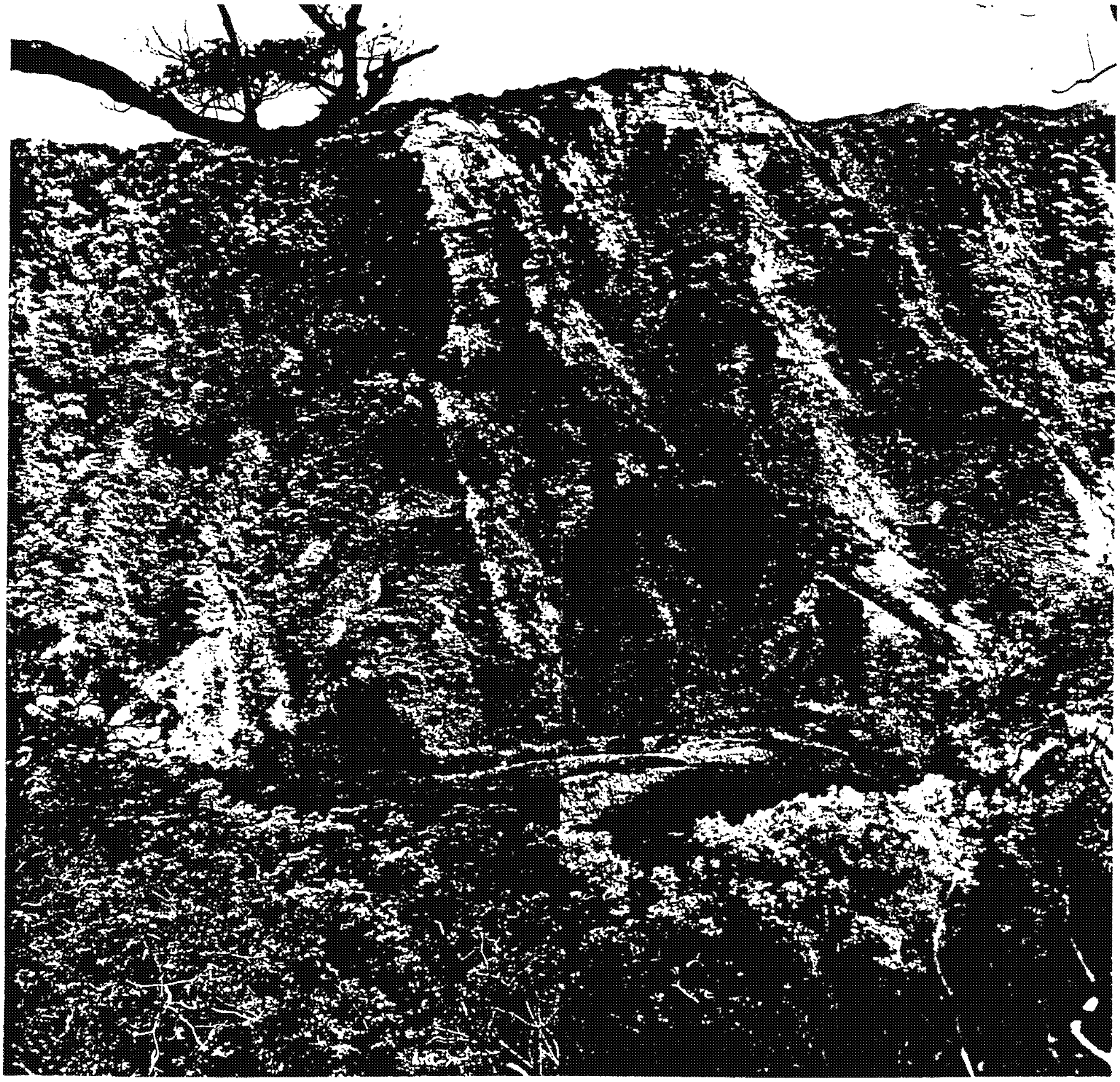

Figure 8 - View of full height (1100 feet) of northwest wall of Moanalua Valley, from mid height of opposite wall. Negative No. 21333-4.

Figure 9 - Panorama looking inland in South Halawa Valley from point on boundary of Honolulu and Ewa Districts. At left is view of sliver spur and small valley beyond it. In the bottom of the main valley is a characteristic meandering of the stream channel and alternation of talus spurs. Negatives No. 21240-1.

of the range the broadening head of North Halawa encroaches on South Halawa, so that the latter, for about 1/2 mile of its upper course, drains an area not over 1000 feet wide, and at one point lacks only about 50 feet vertically and 100 feet horizontally of spilling over the common divide and joining a tributary of North Halawa. The head of South Halawa is thus very close to the crest end of the Red Hill ridge, is marked by a slight saddle at 2300 feet, and overlooks almost the middle of the precipitous "cirque" of Haiku Valley. Like Moanalua Valley, South Halawa Valley has a lower portion with some suggestion of a valley flat, a middle portion with marked development of slightly "intrenched" meanders and a head portion with a narrow, somewhat crenulate channel course.

North Halawa Valley in its lower part is narrower than the south branch but widens markedly in the inland part. It has several well-developed tributaries on the north side, and one on the south, as well as a pronounced branching in the headward part where it drains at least $1\frac{1}{2}$ miles of the range crest. (Figure 10) Like South Halawa Valleys and others, its bottom shows the three sections describe above. Between North and South Halawa Valleys is a flow-slope facet with an apex at 1152 feet, and south and inland from this point is a belt of ridges with somewhat subdued topography, separated by a number of tributaries to South Halawa. This belt extends inland to another "apex" at 1854 feet, beyond which point the divide between the two Halawa Valleys is a single, narrow ridge.

This belt of more complex topography extending inland from the simpler flow-slope facet is a feature not so common in the Honolulu area but increasingly found in the Pearl Harbor part of the Koolau

Figure 10 - Panorama of middle and head portion of North Halawa Valley showing head tributaries and range crest as well as the inland portion of the deeper section of the valley. Taken from buttress seaward from Puu Uau. Negatives No. 21348-49-50.

leeward slope. It is probably due to the less decisive dominance of major streams in the area where their lower courses are longer and more retarded in erosion by the interference of the Waianae dome and the Pearl Harbor embayment, and hence, where midslope tributaries have had more chance to develop. From this area, two long tributaries go into South Halawa and one to North Halawa. (Figure 5)

AIEA FACET

Northwest of the lower end of North Halawa Valley is the triangular area of the Aiea flow-slope facet, which is about a mile wide along the seaward margin, and which extends inland to about 1250 feet. On it is Aiea Stream, essentially a shallow facet-type stream, but with several branches. Two branches of this stream drain a dissected portion of a more extensive flow-slope area which extends inland to Puu Uau at 1656 feet, beyond which the North Halawa-Kalauao divide becomes a simple ridge. This Aiea facet is the last section of the mountainous area to be dealt with here.

THE SALT LAKE CRATERS

The Salt Lake craters form the dominating part of a peninsula which with a width of about 3 miles, extends more than five miles seaward from the margin of the range in the Moanalua-Halawa sector. This peninsula borders the Pearl Harbor entrance channel, through which all drainage from Red Hill to the Schofield saddle passes. Building of the craters by explosive eruptions materially narrowed the original bay between the Koolau and Waianae domes, and, in conjunction with the growth of coral reef, was an important factor in the forming of a broad coastal plain, broken only by the arms and the entrance to Pearl Harbor.

Salt Lake crater is a nearly circular, somewhat compound rim with elevations of 100 to 150 feet on the south and east and with various peaks up to 200 or 300 feet on the west and north, where its tuff is merged with tuff from the adjacent Aliamanu Crater. (Figure 7) On the west of Salt Lake and south of Aliamanu Crater is a broad and massive accumulation of tuff with elevations up to nearly 300 feet, possibly representing additional vents. The mean diameter of the Salt Lake rim crest is about 1 mile.

Aliamanu Crater rim is over a mile long on an east-west axis and scarcely more than half as wide. It adjoins the northwest side of the Salt Lake crater, and the two together are banked against the margin of the Koolau spurs on the two sides of Moanalua Valley to form a saddle at Red Hill with an elevation of 297 feet. This accumulation probably originally raised the possible outlet for Moanalua Stream to not much less than 200 feet. The various consequences of this disturbance will be discussed elsewhere. Aliamanu Crater has low points in the rim on the east and west and peaks of 375 on the south and 485 feet on the northeast side. The bottom of the bowl of Aliamanu Crater is slightly less than 50 feet above sea level.

Makalapa Crater is about a mile west of the Aliamanu rim, and its bottom originally reached to sea level. It is in the process of being artificially filled. The rim reaches 100 feet at some points. it is somewhat elongated in a north-south direction with an average diameter of about a half mile. The three craters mentioned, as far as we know, were built from offshore vents on a rock platform probably only a few feet below sea level; but they form an area roughly 3 miles in diameter which has been built to elevations from 30 to 485 feet above present sea level, in contrast to the fringing reef flat with elevations mostly under 15 feet.

Salt Lake was practically at sea level in the early days of white settlement and was a source of crude salt, since its water was subject to marked evaporation. The salt often formed in large crystals which became rounded to spherical pills, 1/4 to 1/2 inch in diameter, and specimens of these are preserved at the Bishop Museum. For this reason, no doubt, it was commonly supposed that the lake was connected with the ocean. Both Dana and Brigham, however, concluded that the lake had no direct connection with the ocean, a conclusion which has been accepted by Stearns (1). The latter believes that the rise of

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(1) Stearns, H. T., Op. Cit., p. 129, 1935.

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ground water during rainy seasons furnished the water to the Salt Lake basin and that concentration by evaporation was responsible for the formation of salt. This interpretation does not seem immediately convincing to the writer, because the inflow from ground water involves some consequences that seem not to have been met and is not a process completely analogous to the inflow of surface water from streams or springs to desert basins, to which Stearns refers. The writer proposes to discuss this problem elsewhere and will not expand it here, except to say that he believes the accumulation of salt in Salt Lake to have had more intimate relationship to the ocean than any of these previous writers conceded.

In 1919, Well No. 157 was drilled near the north shore of Salt Lake and has discharged into the lake raising its level to around 15 feet above the sea and freshening it to a composition suitable for fish culture.

FORT SHAFTER TERRACE

The remainder of the coastal plain area may be classified as follows: remnants of Fort Shafter terrace with elevations chiefly from 70 to 120 feet, emerged coral reef with or without a slight veneer of tuff at elevations of 5 to 20 feet, and marine or alluvial shore flats or valley bottom areas chiefly at under 10 feet but extending up to 50 feet or more in the valleys.

The Fort Shafter terrace fringes the ends of Koolau dome spurs between Middle Street and the lower flats of Moanalua Gardens. The eastern part is underlain by lava flows of Kalihi basalt. The Hawaiian Ordnance depot and the Fort Shafter post are chiefly built on it. Remnants of the same terrace are found in lower Moanalua Valley, in lower Halawa Valley, and at several points westward to Aiea. It is mostly composed of gravel, including layers of alluvial tuff which will be described below.

DRAINAGE PATTERN

The inland drainage pattern of this area is similar to various other segments. North Halawa Stream is a dominant through stream with a number of important tributaries and a broadly branched drainage pattern at its head. (Figure 5) Moanalua is only slightly less mature in its development of head branches and more mature in erosion of its bottom. South Halawa Stream has several short branches at a point about a mile from the crest but has only a single tributary reaching the crest. Manaiki Stream has a notably long course with but one long tributary. (Figure 11) Kahauiki and its shorter branches end headward, against the northwest divide of Kalihi Valley.

In the lower courses, nearly every stream has been modified or diverted by the tuff of the Salt Lake craters. The various branches of Kahauiki were probably independent channels to the ocean prior to the Salt Lake eruptions. Kahauiki was forced southward and acquired the other channels as branches. Moanalua Stream undoubtedly went directly into the ocean, as did Manaiki Stream. The Salt Lake crater formed a nearly complete barrier to Moanalua Valley and forced Moanalua Stream to find its way southward along the ends of the rock spurs, where it has cut the Moanalua Gorge, partly in tuff and partly in Koolau lava flows. Moanalua Stream then joins Manaiki Stream, and the two probably first had a higher course on a more extensive Fort Shafter terrace and subsequently have developed a valley flat nearly half a mile wide, graded in relation to present sea level.

The two Halawa Valleys doubtless had separate courses to the sea originally, but with the encroachment of the Salt Lake crater mass, plus the grading of the valley mouth to the Fort Shafter level, the streams became merged and have remained so.

Climate

Sufficient indication of the climate of the Honolulu and Pearl Harbor areas has been presented elsewhere. Annual rainfall in the area covered by this report is shown on the isohyetal map of Figure 12.

Figure 11 - Panoramic view of middle section of Manaiki Valley, and northwest wall of Manaiki. Horizon at left is Waianae Range, with a peak of Salt Lake Crater; in middle part horizon is profile of flow slope facet toward Moanalua. Negatives No. 21316-7-8-9.

The maximum rainfall shown is in excess of 170 inches, and the average of the mountainous area which furnishes infiltration to the basal water system is about 142 inches. Unfortunately, few gages or records of long periods are available for the area west of Kalihi, and the isohyets shown do not have an accuracy consistent with the scale even of reproduction in Figure 12, and much less so with the scale at which the areas and rainfall quantities were measured. Hence, while in the larger part of the Honolulu area the local errors of the mean annual rainfall are possibly not over 10 inches and the over-all, estimated mean not in error by more than 5 inches, the corresponding errors in the Moanalua-Halawa district can easily be as much as 40 inches and 15 or 20 inches.

Vegetation and soils, settlement, etc.

The soils of the various parts of this district are similar to those of other leeward districts, except insofar as the tuff of the Salt Lake craters has produced modified soil conditions in the extensive coastal area. Sugar cane is grown extensively in this area, and there has been an increasing amount of military utilization and building in the entire seaward half of this district, including the lower parts of the range spurs.

On the flow-slope facets, pineapples are grown on those southeast of North Halawa Valley, and sugar cane is grown on the Aiea facet west of Halawa. All the facet area of Kahauiki, between Kalihi and Manaiki, has been included for many years in the Fort Shafter reservation. Dairying is carried on in lower Manaiki Valley. Much of the

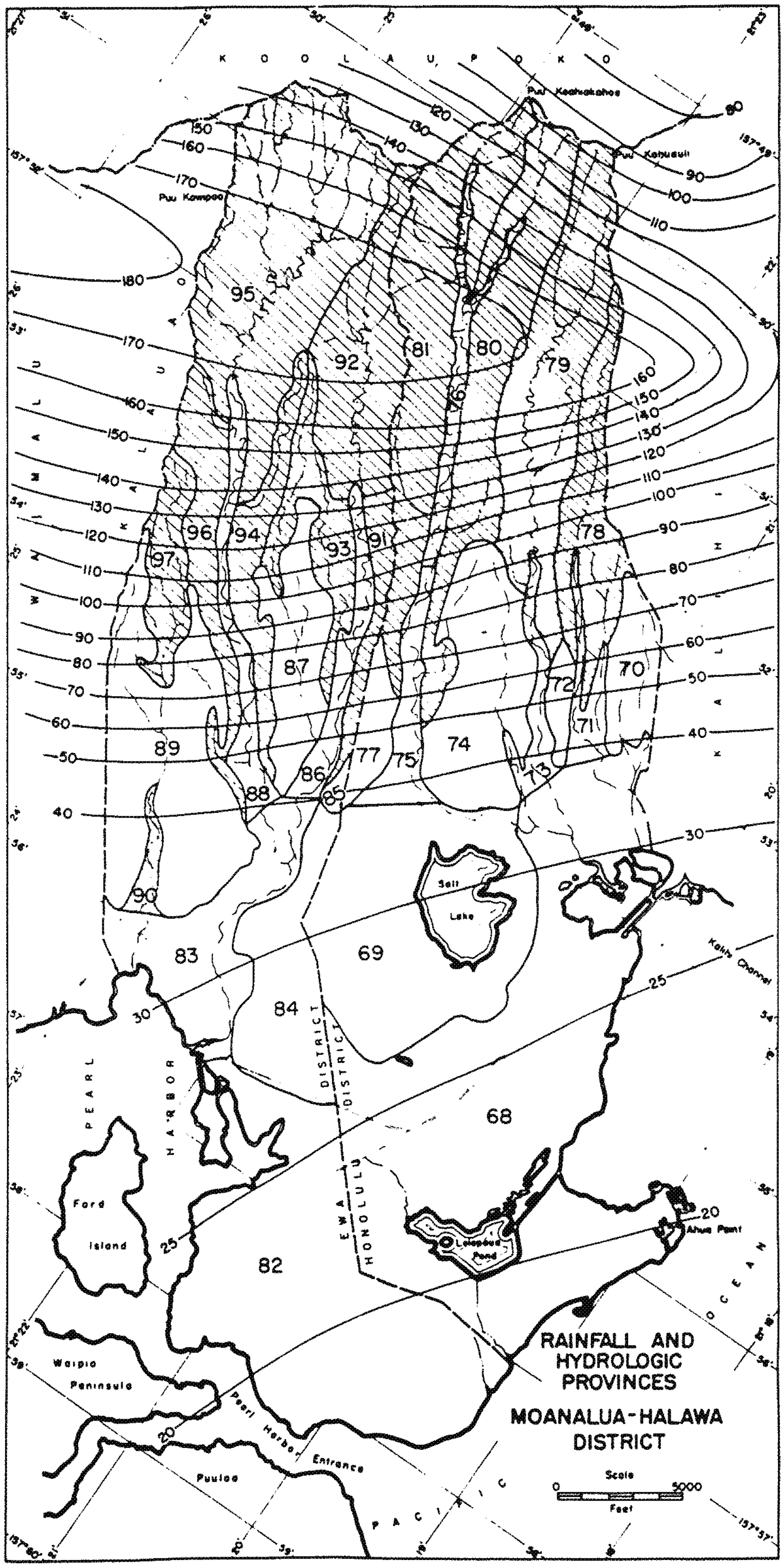

Figure 12 - Isohyetal Map of Moanalua-Halawa District, showing hydrologic provinces. (Tables, pp. 96-98, this report.) The shaded portion indicates the maximum area from which infiltration is believed to effectively reach basal water. Rainfall data from U. S. Weather Bureau, via Territorial Planning Board, 1939 and 1940.

higher part of the Salt Lake crater group has a surface showing bare rock, with a scattered vegetation cover of cactus, kiawe, lantana, and other thorny shrubs. The terraces and valley bottom of lower Moanalua are used for the Moanalua golf course. The upper part of the Moanalua Gorge is now the site of extensive quarrying operations, and additional quarries have been started on the west side of Moanalua. An extensive quarry is also located in the end of the spur between the Halawa Valleys.

Moanalua Valley once had a paved road with at least 10 bridges crossing the stream, which extended more than 3 miles inland. These improvements were built by the Damon family, owners of this drainage basin. The road in its inner part is no longer usable because of flood damage to bridges or approaches. The bridges were of various designs in concrete and masonry but did not have adequate underpass capacity to handle the exceptional floods which may come in any stream of this region, and they failed by various means, undermining, erosion of approaches, and overturning of all or part of the bridge. Taken as a whole, they furnish a very interesting lesson in local, small-scale construction.

Moanalua Valley flat, below the gorge, is the site of the Moanalua Gardens, landscaped and planted as a park and nursery. This was dedicated as a park, for the enjoyment of the public by S. M. Damon many years ago, and arrangements were made for its perpetual care.

The most inland settlement in the area is on Aiea Heights where numerous residences of persons of Honolulu or Pearl Harbor employment have been built, up to nearly 1000 feet in elevation.

There is a small cabin continuously occupied in North Halawa Valley about 3 miles inland from the main highway, and a residence is kept in condition in Moanalua Valley nearly two miles inland. In Moanalua, the ranger's family lives at a house about 1½ miles inland from the highway. There is also a cabin owned by the Damon family on the ridge southeast of Moanalua at about 1500 feet and nearly 3 miles from the highway. This structure, however, is in disrepair and has not been used for some years.

The mountainous area in the several valleys shows similar characteristics to those described elsewhere. Moanalua Valley, more than others, which has been visited and open to some grazing for many years, has more grassy area and more scattered exotic trees and shrubs. At present there are four horses and a few cattle, which occasionally range to the extreme head of the valley to graze at a point overlooking Haiku Valley. In Moanalua, spotted deer of the Japanese variety have been running wild for a number of years but seem not to have spread to adjacent mountain valleys. At present they are more abundant, or at least are more commonly seen on the lower ground around Red Hill and Salt Lake, and they are occasionally killed by automobiles on the highways. Protection against trespassers has also led to considerable increase in wild pigs, which seem to be more abundant in Moanalua than in any other valley visited by the writer.

There are fairly good trails on the various ridges of Kahauiki, inland from Fort Shafter for some distance, but any of these are often somewhat overgrown and in need of trimming in the inland section. The ridges on the two sides of North Halawa Valley have excellent dug trails built by the Civilian Conservation Corps several years ago, which are still in very fair condition. The bottoms of Moanalua, and both Halawa Valleys are fairly open to travel for several miles inland, and cattle trails in Moanalua facilitate travel on foot to the crest of the head saddle. Manaiki in its inland part becomes increasingly overgrown, and travel is impeded by numerous deep-cut meanders as well as vegetation. Its head is the most difficult of access of any part of this area.

The inland portion of this area is included within the Territorial Forest Reserve. The ownership of land is shown in Figure 13. Some of the tracts are under the jurisdiction of the Division of Forestry on a tax-free basis; the owners of others, particularly Moanalua, have elected to pay taxes and to make the land available to the Forestry restrictions only in part. There is no water supply reservation in this section, the Honolulu Watershed Drainage Reservation being limited to inland Kalihi and valleys eastward. (Figure 14)

GEOLOGY

General Geology of the Koolau Range

The general geology of the Koolau Range has been described elsewhere. Such additional findings as have come from study of this district will be summarized as differences, for comparison with the general conditions elsewhere. It seems clear from the geologic survey of this area that both dikes and sills are relatively less abundant in the main part of the leeward slope west of Nuuanu than east of it. Fewer intrusive bodies were found in Kalihi than in Nuuanu, and fewer in Moanalua and Halawa than in Kalihi. (Figure 15)

Apparently the same is true of tuff beds. Very few were found in the district under discussion. Throughout the Moanalua-Halawa area, the general structure of the range, made up of thin basaltic lava flows, is similar to that farther east.

The Koolau formation

BASALT FLOWS

The larger part of the mountainous, inland part of this district is immediately underlain by basaltic lava flows in place. (Figure 15) These are generally exposed in the middle slopes of the steeper valley walls and in the lower slopes at the points where the streams swing against any particular wall. In the upper margins of valley walls there is often a slightly less steep slope and a moderate thickness of basaltic residuum either in place or moved slightly down the slope.

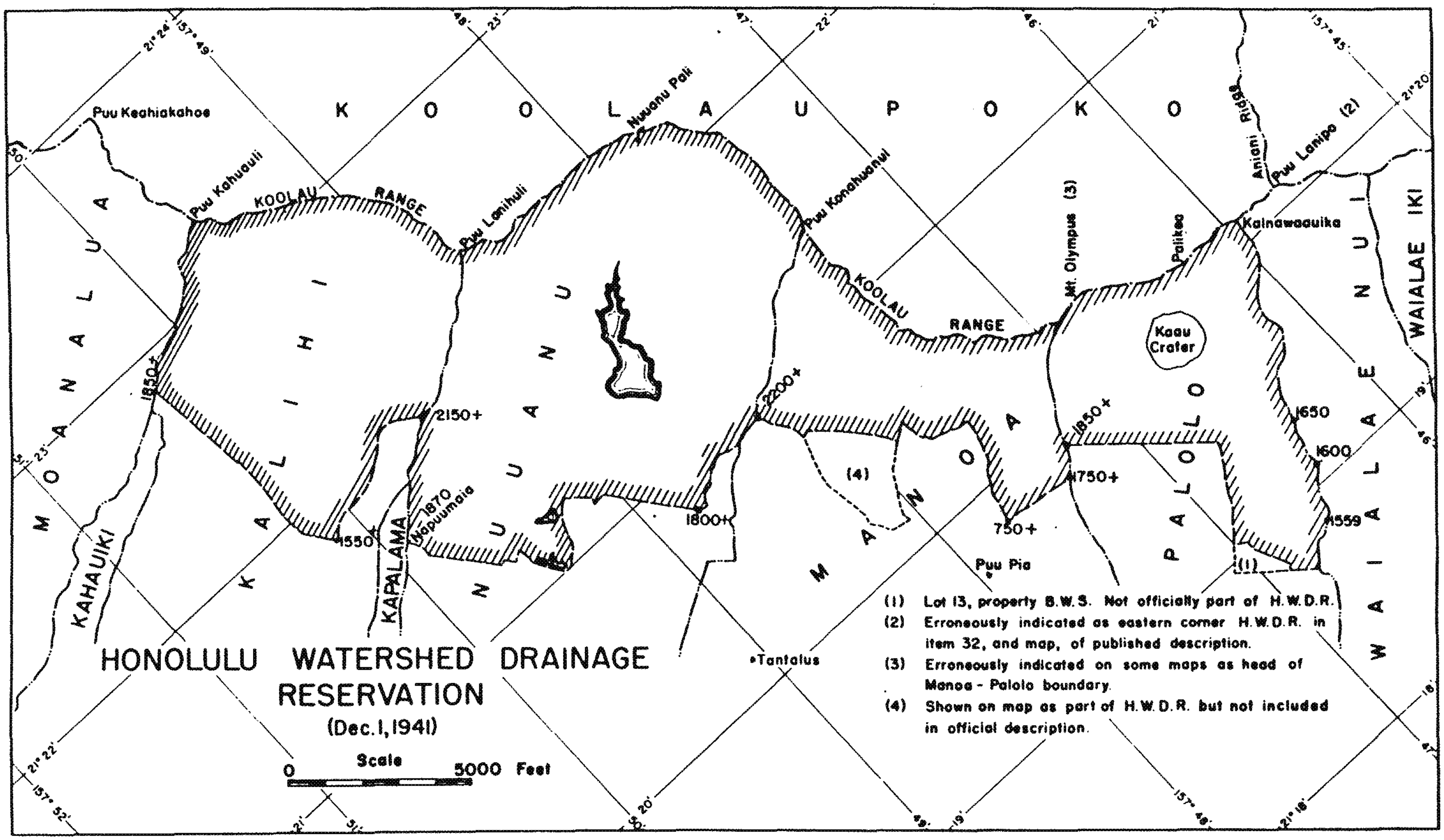

Figure 14 - Sketch map showing existing boundaries of the Honolulu Watershed Drainage Reservation, together with notes on certain exceptions. Data from "Regulations of the Division of Forestry", Board of Commissioners of Agriculture and Forestry, Territory of Hawaii, effective December 1, 1941.

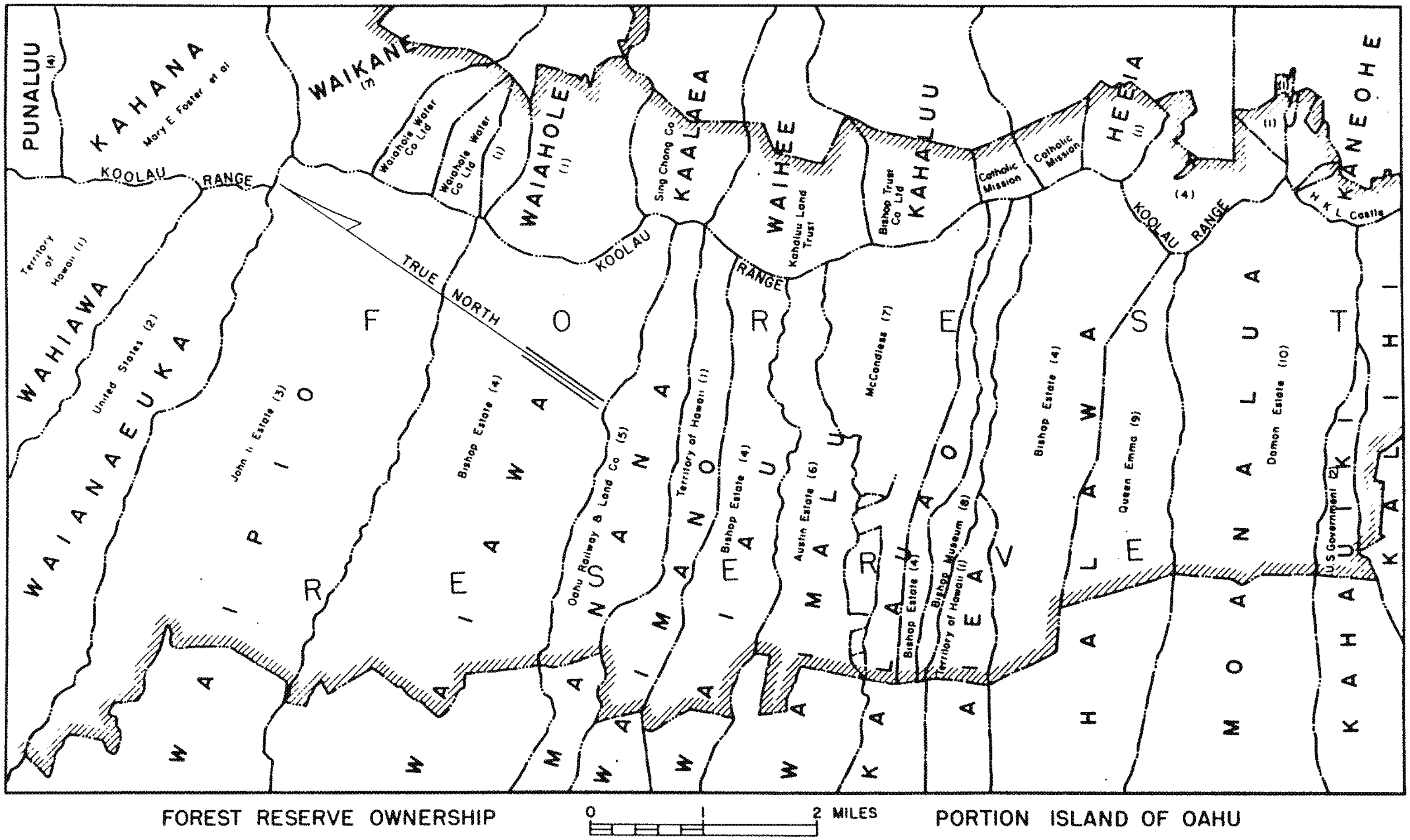

Figure 13 - Sketch map showing Forest Reserve ownership on the Koolau Range from Kalihi to Wahiawa. Most of this land is under the jurisdiction of the Division of Forestry under Regulation 1, but in some areas where owners elect to pay taxes, only a part of the provisions of Regulation 1 are in force. In Kalihi, and in parts of the Waiahole-Waikane area are Water Reserves, boundaries not shown.

Figure 15 - Geologic Map of Moanalua-Halawa District, Oahu. Scale 1 inch equals 500 feet. Working map on double weight, bromide enlargements from U.S.G.S. photolithographs, in sections 1 minute of latitude (6060 feet) by 3/4 minute of longitude (4260 feet). (No copies yet made)

Along the tops of ridges, where these are more than 5 or 10 feet wide, the basaltic residuum is commonly 5 or 10 feet thick, and on the wide parts of flow-slope facets this residuum may be 25 to 50 feet thick, with hydrologic properties radically different from those of the basalt flows when fresh. (Figure 16)

An attempt has been made to map as residuum those areas where the residuum occurs continuously over areas of several acres, but because of the intimate transition from basalt to residuum and practical difficulties of categorical discrimination of one from the other, no great fidelity of detail can be claimed for the boundary. However, it is believed that the broad pattern of fairly wide areas from which infiltration does (the basalt), and does not (the residuum), reach the basal water body, is sufficiently valid to be very important, both as to its actual pattern and also the total areas contained in each category.

Similarly, on the valley sides, the decision as to whether to map bedrock or detritus is a very difficult one. In some areas, it is evident that fairly sound bedrock underlies the whole surface at less than 5 feet in depth, meriting mapping as bedrock lava flows. In other areas of a few acres, the cover of detritus in a fan may be so continuous and the configuration such that it is most likely the detritus is prevailingly 20 or more feet thick. Such an area, in its hydrologic significance, is properly mapped as intermediate alluvium when on the steep inland slopes. To map a boundary so sporadic as that between these two conditions, everywhere within 50 or 100 feet, and to discriminate such on grounds that would be duplicated in detail by another observer would require vastly more time than has

Figure 16 - Panorama of north wall of North Halawa Valley from south wall near line of pipeline tunnel. The site of the Halawa Basal Shaft now under construction is approximately at the right hand limit of the sugar cane field. The characteristic stratification of the lava flows is shown by the dark ledges sloping at a low angle from right to left. Negatives No. 21143-4-5-6.

been available in the present study. On the other hand, there is considerable local similarity from spur to spur, or chute to chute, on a given valley wall, as well as some difference between the mantle rock, and bedrock relations in one valley as compared to the next. On all the mountain traverses which have been made, an effort is made to record the prevailing condition and map such generalized boundaries as are evident. It is not possible to examine the ground of every acre of the terrain. (Figure 17) But in a broad way, some part of every square mile has been visited, and usually some direct observation has been made on every 40 acres or less. The mapping of all the terrain has been based on the local sampling actually done, which is considered vastly superior to any general office mapping of the mountain area which might have been done on the basis of information taken from previous maps and trail trips only. The general validity of the bedrock mantle rock pattern is superior to the specific accuracy of the boundaries at any given point.

From the standpoint of behavior of ground water in deeper percolation or flow in the basal water body, the unbroken occurrence of Koolau rock in the mountain area, including practically all the area under the valleys also, is the important fact. On the other hand, with reference to infiltration, the discrimination between somewhat fresh, well-exposed lava flows and the much weathered, compact mantle rock, whether basaltic residuum or transported, detrital material is extremely important, despite its difficulty. Consequently, this discrimination has been made in as much detail as possible, both by direct observation and by interpretation of types of slopes based on the prevailing local condition.

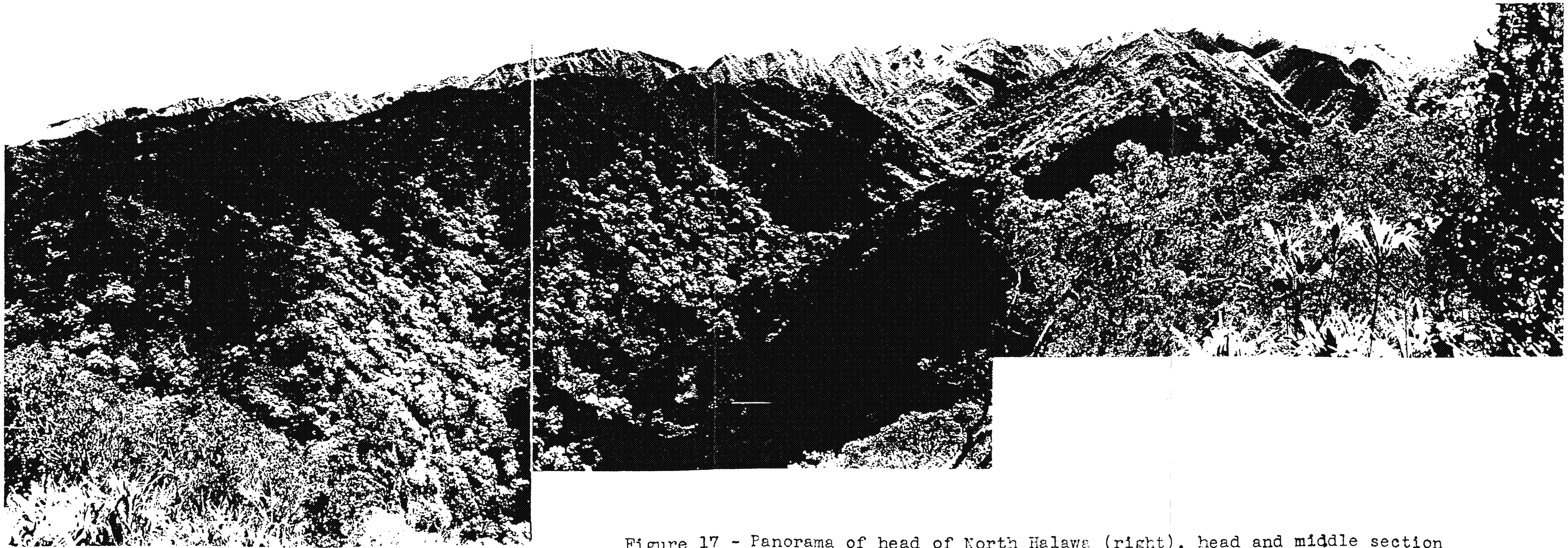

Figure 17 - Panorama of head of North Halawa (right), head and middle section of Kalauao Valley and crest of Koolau range to the northward showing general character of mountainous watershed. Negatives No. 21351-2-3.

As in the other areas, the Koolau basalt passes beneath all other formations, and forms by far the greater part of the mass at any considerable depth below the surface. At the ends of most of the spurs in the Honolulu area, the Koolau rock has been eroded to a slope much steeper than that of the lava flows and passes under the coastal plain formations along the line of a former sea cliff. Somewhat below sea level the rock surface flattens off to form a pavement on which the coastal plain formations are laid. The form of this surface is not well known, but it probably is of gentle slope near the base of the cliff, steepening again to something like 500 feet to the mile, since the Koolau rock surface under Diamond Head, 2 miles from the cliff line, is apparently more than 1000 feet below sea level. In the Fort Shafter-Moanalua area the steepened ends of spurs are overlapped by Fort Shafter gravel and by Salt Lake tuff and are not generally exposed below an elevation of about 100 feet. In the Red Hill spur, the form of the end of the mass of Koolau rock is not exposed, but in Artesian Well No. 160, on the northwest inside slope of Aliamanu Crater, 3000 feet southwest and down the spur axis from Red Hill saddle, Koolau rock was encountered at about 20 feet below sea level. The surface of the Koolau formation in this area, from Halawa westward, is covered by thick residuum down to sea level, whereas in the Honolulu area the residuum on the flow-slope facets is chiefly stripped off below three or four hundred feet in elevation, suggesting that there has been relatively much less erosion of the coast and of the lower ends of spurs in the Pearl Harbor area than in the Honolulu area. Some of the probable consequences of these differences will be discussed below.

The Koolau series in the Moanalua-Halawa area, as elsewhere, consists of upward of 3000 feet of thin lava flows lying at dips of 4 to 7 degrees. The lava flows of the upper 1000 feet of this section are fairly well known from the numerous exposures in the walls of the lower ends of the valleys, but the deeper parts are mostly concealed. In practically all the exposed parts there is a predominance of aa flows, though it is perhaps rare that any section of 100 feet will be wholly without pahoehoe flows. (Figure 18) In the lower walls of North and South Halawa Valleys, for the first mile inland, and up to a few feet above the valley bottom is a section conspicuous for a preponderance of pahoehoe flows. Immediately above this series, however, there are found several thick aa flows, forming a mass more than a hundred feet thick which is conspicuous for the thickness and massiveness of flows and in which the quarry at the end of the dividing spur is located.

A part of the same series is encountered in the west portal to the pipe line tunnel of the Board of Water Supply through Red Hill, and in this tunnel practically the whole length is in aa flows, or in thick clinker mounds which accompany aa flows and which by their thickness and ruggedness would indicate thick aa flows if they were not otherwise exposed. All these indications show that the Koolau flows of the seaward parts of the Koolau Dome in the Moanalua-Halawa area are preponderantly aa flows. The same indication was found in the exploration holes which were diamond-drilled in the Red Hill ridge in connection with subsurface construction operations.

Everywhere in any extended section some pahoehoe flows are found, but nowhere was a section of say half the height of a valley

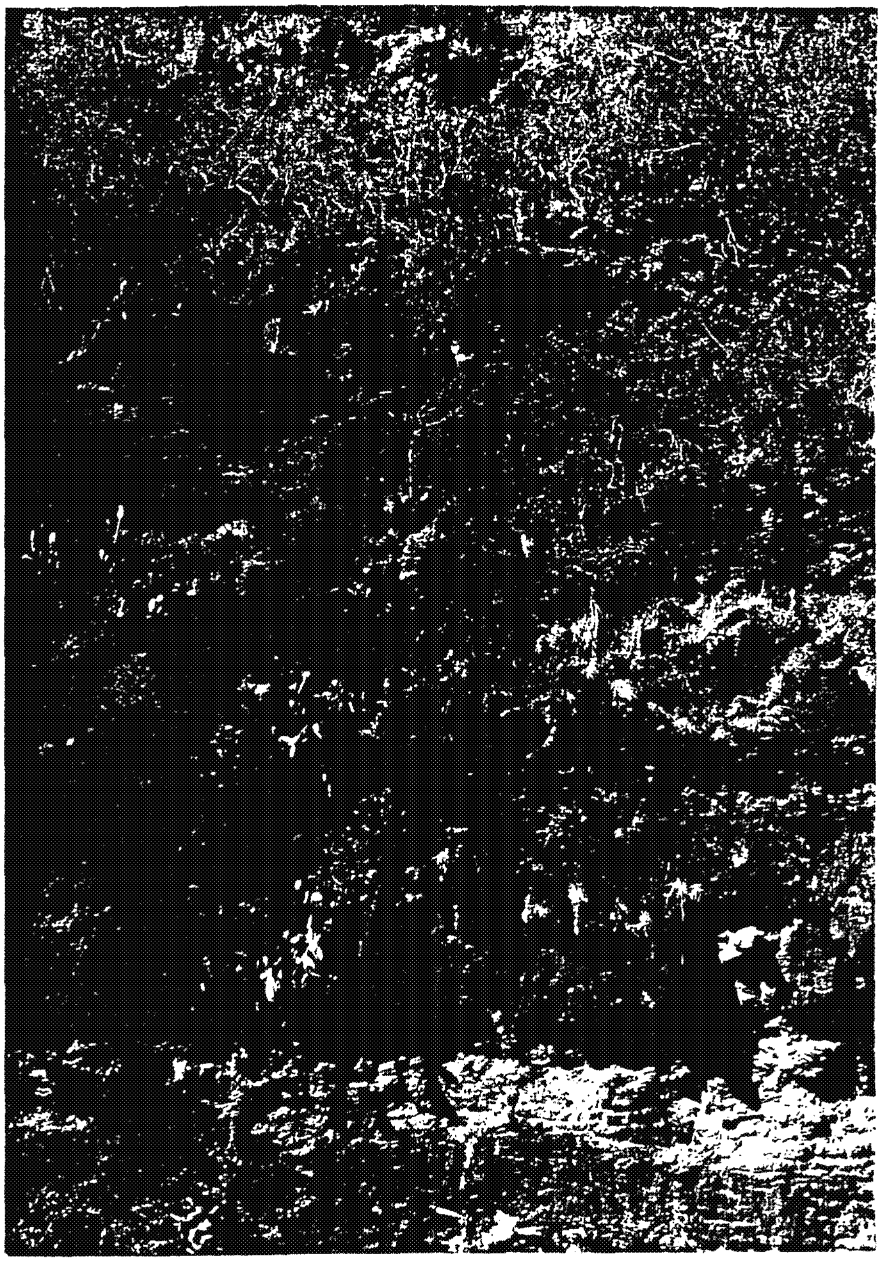

Figure 18 - Section of north wall of Manaiki Valley showing both aa and pahoehoe flows of the Koolau series. Negative No. 21295.

wall, such as 250 feet or more, found in which pahoehoe flows were preponderant. If such a condition obtains in the inland portion nearest the original vents, the rock is not exposed with sufficient continuity to demonstrate it.

The aa flows, when seen in cross-section, consist of dense, interior parts, with loose, clinkery, scoreaceous layers both above and below. Those who have seen lava flows in process of eruption and placement on Mauna Loa or Kilauea have seen that the fronts of moving lava flows rarely show any wide or general exposure of liquid, incandescent lava, but are more commonly deeply covered by an extremely rough, rugged accumulation of rough, clinkery, encrusted fragments of newly solidified, hot lava from fist size to the size of a 10-ton truck. This mass is mostly not even red hot and often almost completely conceals the incandescent, liquid tongue of lava beneath. The latter continues to move downslope, showing through various cracks and openings especially at night, in a way that is very conspicuous. With the continued motion of the hot, molten interior, the outer part is carried forward, and the loose clinker tumbles and slumps down the frontal slope which is maintained at the angle of rest, perhaps 35 to 40 degrees Occasionally a tongue of white or red hot liquid breaks out clear of the detrital cover, but such a tongue after some cooling is usually soon covered by the clinker. With such behavior, it is apparent that nearly all the terrane over which the flow advances is covered by a very irregular layer of the solidified clinker which tumbles down the frontal slope, before any of the liquid lava of the flow is placed. Thus, both a basal layer and a top layer of clinker of the same flow is usually, with but few breaks, deposited in addition to the dense interior part of the flow.

In advancing over an irregular terrane, perhaps the rugged surface of a previous aa flow, it is natural that the tumbling clinker should fall and be shoved more thickly into the hollows than onto the summits of the earlier surface and that the floor on which the aa flow proper is deposited would be slightly less rugged than the top of the previous lava flow. However, there may be many exceptions to this, and sections of aa flows often show the dense part poured down over declivities of 10 to 20 feet and following other irregularities of the earlier surface.

Though it is usually not easy to distinguish between the top clinker of one flow and the bottom clinker of the next overlying flow, it is thought that the top clinker is usually thicker than the bottom clinker. Because of the difficulty of distinguishing one clinker from another, the whole section of a succession of aa flows appears as an alternation between clinkery parts and dense parts. In perhaps the majority of sections seen in the Koolau Range of Oahu, the dense parts are at least as thick as the combined clinker portions, but it is not uncommon locally for the clinkery parts to form mounds or thick lenses two to four times as thick as the adjacent dense flows. In other places the clinkery layer between two flows may locally pinch out to practically zero, though the contact is usually quite distinguishable.

The dense parts of the aa flows usually show only scattered, large, irregular vesicles, with considerable parts free of noticeable voids. Such vesicles as are present may roughly mark out broad lines of flow, but often do not. The dense parts are broken by cooling cracks normal to the plane of the flow into blocks which are not much longer or wider than their thickness in the thinner flows and relatively shorter and narrower, perhaps less than the thickness of the flow in the thick flows. Total thickness of the combined clinker layer and dense part of many aa flows is less than 10 feet, perhaps the average falls in the range 10 to 20 feet. A section exposed in the south wall of North Halawa Valley in the presently operated quarry is notable in the presence of three exceptionally thick flows which total at least 100 feet. The north wall here is similar. (Figure 19)

Pahoehoe flows represent the more primitive condition of the molten lava on eruption, and they solidify as frothy tongues and pools, commonly with a vesicular, glassy crust often wrinkled into what is aptly called "elephant hide" configuration. Except for the readily broken glassy crust, there is no clinkery detritus; and the banded, often highly vesicular flows with complex doubling and infolding of the vesicular banding, are laid one directly on another. Surficial weathering of the pahoehoe flows is more rapid than that of the dense parts of the aa flows. Moreover, the lack of flows of marked resistance in a pahoehoe series is unfavorable to conspicuous exposure of any single bed. Hence, in the inland area where there are fewer exposures, the more important outcrops are the thicker aa flows, though in a cliff exposure showing continuous, the pahoehoe flows also appear.

The pahoehoe rock is relatively unsuitable for most commercial rock purposes, since it not only has so large a percentage of voids as to be much lighter than the other rock, but it also is more troublesome at every stage of working, making more dust and waste in crushing. It is also more troublesome in blasting, since the effect of explosives is dissipated throughout the porous mass instead of initiating the desired rifts. Hence, though some pahoehoe may be unavoidable in any

Figure 19 - Thick aa flows near base of north wall of North Halawa Valley seaward from Halawa Shaft. Negative No. 21452.

extensive quarry operation, and though aa clinker is also waste in a quarry operation, the most desirable quarry rock consists of one or more thick, dense aa members, in a position where a minimum of overburden, aa clinker, or pahoehoe flows need be handled. Though some parts of the Koolau series meet this condition fairly well, it cannot be expected in general that unbroken masses of quarry rock in the Koolau series will be found so large and free from detrimental material as occur in some of the valley-filling masses of basalt of the much later Honolulu series which has been quarried so successfully in the Moiliili quarry. The latter rock not only solidified under conditions more favorable to the formation of thick masses but is also of a markedly different chemical composition and appears to crystallize in naturally denser masses.

Several years ago, a quarry was opened in the end of the Koolau spur facing the Salt Lake crater, just east of Moanalua Valley. This quarry has been intensively operated in recent months and has been supplemented by the opening of a new quarry on the north side of Moanalua Valley, inland from the golf course. A large amount of rock has been excavated from quarries around the end of the spur between the two Halawa Valleys. All these quarries testify to the presence of somewhat thicker and more suitable aa lava flows than would be found in random quarrying in the Koolau mass.

As has been stated elsewhere in these reports, the Koolau lava flows are feldspar basalts having intergranular-porphyritic texture as the normal condition with variations toward equigranular or felty matrix textures, or toward intersertal-porphyritic texture when a certain amount of glass is present. Phenocrysts when present are usually olivine, orthorhombic pyroxene, or plagioclase in any combinations or proportions. The groundmass minerals are feldspar (probably sodic labradorite), olivine, rhombic pyroxene, augite, opaque ore minerals, minute amounts of apatite, and in some specimens, glass. The foregoing brief summary is based on a more lengthy summary by Winchell (1).

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(1) Winchell, H., (In Wentworth and Winchell Ms.) The Koolau Series, Manuscript, pp. 31-35, 1941.

Perhaps the most distinctive rock in the whole Koolau basalt series is the Moanalua feldspar porphyry phase, which is best known in Moanalua, but is also found in Halawa and in Haiku Valley on the windward side of the range. This is a basalt porphyry in which at least half the mass consists of tabular feldspar phenocrysts 1/2 inch to over an inch in diameter and usually less than 1/10 inch in thickness. The phenocrysts are rudely oriented with their two longer dimensions approximating parallelism to one plane. Owing perhaps to the large area of the phenocrysts, to their almost complete breaking of continuity of the matrix and to the marked cleavage of the feldspar, the rock is very readily shattered, and it is practically impossible to trim out a hand specimen to good form. This friability is also enhanced by the much weathered condition in which much of the rock is found. This rock is found in place in a number of localities at low elevations in Moanalua Valley, at several points higher up and near the head of the valley and also in similar localities in Halawa and Haiku. It is abundant in the stream-borne gravel of Moanalua and less so in other valleys.

A specimen of this rock has been transmitted for chemical analysis, which will indicate whether its chemical composition differs significantly from that of other Koolau flows, but this analysis has not yet been made and is probably delayed by war conditions. Up to the present writing, all chemical analyses of the Koolau basalt which have been made, have confirmed the impression gained by the microscopic examination of some hundreds of thin sections to the effect that the whole series from the lowest accessible flows to the latest and highest, show very slight variation in composition and no discernible trend or differentiation.

TABLE OF ANALYSES OF ROCKS OF SOUTHEASTERN OAHU (1)

	KOOLAU LAVA					HONOLULU SERIES LAVA							
	9948	9991	9986	10396	9980	9962	10402	9982	10399	9961	9960	10400	10401
	Makapuu	Manoa	Haiku	Waia-hole	Waimea	Koko	Kalama	Black Point	Kaau Waiomao	Nuuanu	Kalihi	Train-ing Sch.	Puu Hawaii-16a
SiO_2	49.62	50.08	50.59	48.74	50.97	45.13	43.94	42.86	36.72	38.57	36.75	37.10	37.22
TiO_2	1.51	2.08	2.18	2.42	2.14	2.94	2.32	2.94	2.82	2.79	2.41	2.90	2.02
Al_2O_3	12.68	15.80	15.34	15.98	13.72	16.40	12.60	11.46	11.56	11.71	11.98	11.12	12.08
Fe_2O_3	3.21	3.58	2.23	4.14	2.39	3.42	3.84	3.34	4.94	5.21	6.05	6.53	5.18
FeO	7.60	7.81	8.18	7.16	7.61	8.17	9.18	9.03	8.17	7.78	7.45	7.31	7.88
MnO	.09	.11	.09	.06	.11	.07	.09	.13	.13	.11	.08	.09	.11
MgO	13.86	6.70	7.64	6.96	10.18	5.52	11.43	13.61	13.27	13.08	12.08	12.81	12.71
CaO	7.48	9.92	9.60	9.90	8.51	11.30	10.78	11.24	14.34	12.84	13.81	13.56	13.34
BaO	None	None	None	None	None	.06	.08	.04	.11	.08	.13	.13	.12
SrO	None	None	None	None	None	None	None	None	None	None	None	None	None
Na_2O	2.36	2.36	2.68	2.77	2.56	3.62	3.84	3.02	3.93	4.22	4.75	4.56	5.12
K_2O	.15	.17	.11	.22	.61	1.02	1.02	.93	.62	1.20	.91	1.20	.71
H_2O-	.34	.28	.27	.70	.08	.42	.02	.12	.41	.19	.36	.04	.23
H_2O+	.67	.74	.64	1.19	.61	1.16	.36	.44	1.63	.59	1.61	1.11	1.73
CO_2	None	None	None	None	None	.05	None	None	None	.27	None	None	None
P_2O_5	.04	.12	.15	.08	.28	.66	.43	.52	.82	1.11	1.41	1.19	1.40
SO_3	.02	.06	.07	.09	.06	.07	.21	.09	.31	.07	.07	.34	.17
Cr_2O_3	.19	.06	.05	.04	.07	None	None	.04	.07	.06	.03	.04	.03
	99.82	99.87	99.82	100.45	99.90	100.01	100.14	99.81	99.85	99.88	99.88	100.03	100.05
Sp. Gr.	3.09	3.02		3.06	2.99	3.03	3.14	3.19	3.10	3.23	3.10	3.19	3.14

(1) These analyses made by F. A. Gonyer, with compensation from the Geological Society of America Project Grant 297-39, awarding $1000 to the Committee on Hawaiian Petrology for analyses of rocks from Southeastern Oahu and East Maui.

DATA ON ANALYSED ROCK SPECIMENS

Specimen No. (1)	Photo No. (2)	Longitude	Latitude	Locations
9948	288	157°39'42"	21°18'46"	Koolau lava; southeast end of the Koolau Range, Oahu, T. H. Roadcut on windward side below Kings Highway Pass, Makapuu Head. Specimen from road level, 50 feet southeast from lower (northwest) end of cut, and near second manhole cover from west end of cut.
9991	304	157°47'40"	21°19'54"	Koolau lava; south central Koolau Range, Oahu, T.H. Waiakeakua branch of Manoa Stream at top of fall below Wright monument and rain gauge, and between the lowest and the second crossings of the pipeline carrying water from Manoa Tunnel Number 3 to Honolulu.
9986	301-302	157°50'17"	21°24'40"	Koolau lava; central Koolau Range, Oahu, T. H. Elevation 730 feet in left wall of gulch carrying main flow of water to the left (north) fork of Haiku Stream, Haiku Valley, near Kaneohe.
10396	337	157°53'17½W	21°28'29"	Koolau lava, Waiahole Valley, Oahu. From elevation of 890 feet, in channel of small tributary north of first intake north of main tunnel through range.
9980	299	158°04'16"	21°38'26"	Koolau lava; north end of Koolau Range, Oahu, T.H. Near concrete marker on shore opposite Wananapaoa Island, north of Waimea Bay.
9962	294-295	157°41'38"	21°16'33"	Koko lava, Honolulu series; Koko Head, Oahu, T.H. Southwest side of small flow in gulch north of Hanauma Bay at about 130 feet elevation.

Specimen No. (1)	Photo No. (2)	Longitude	Latitude	Locations
10402	340	157°39'52"	21°17'54"	Kalama lava, east of Koko Crater, Oahu. From east side of main highway, north of concrete bridge and south of junction with old private road to Makapuu and about 0.3 mile north of beach.
9982	300	157°47'45"	21°15'30"	Black Point lava, Honolulu series; Black Point, (Kupikipikio), Oahu, T.H. About 30 feet east of the foot of the steps forming a public right-of-wa; to the beach, at the south tip of Black Point.
10399	338	157°47'03	21°18'53"	Waiomao (Palolo) lava, Waiomao branch of Palolo, Oahu. From south bank of road cut 250 feet from inland end of public road, elevation ca. 600 feet.
9961	291-292	157°50'50"	21°19'43"	Nuuanu lava, Honolulu series; Nuuanu Valley, Oahu, T.H. Northwest bank of Nuuanu Stream immediately above Kapena pool.
9960	290	157°50'10"	21°22'12"	Kalihi lava, Honolulu series; Kalihi Valley, Oahu, T.H. Right bank of Kalihi Stream at water reservation boundary, elevation 600 feet. Analyzed sample composed of chips 2 inches or less in diameter, hand sorted to eliminate olivine segregations common in this flow.
10400	339	157°45'40"	21°22'56"	Training School lava, Kailua, Oahu. From road banl east side of Maunawili Valley, about 1/2 mile west and south of Kailua-Lanikai junction on main highway, elevation ca.
10401	-	157°45'30"	21°27'30'	Puu Hawaiiloa lava, Mokapu, Oahu. From quarry neai east side of flow at elevation of 50 feet.

Note (1) Field locations, Board of Water Supply, Geologic Survey Honolulu Watershed.

(2) Field Negative File, H. Winchell, Board of Water Supply.

The foregoing analyses furnish extremely valuable information in the discussion of the fundamental petrologic problems of the Koolau lavas and of the later differentiation by which the Honolulu series lavas were produced. Many of the details revealed are quite beyond the scope of the present report, but it is desirable to point out the elementary differences between the Koolau lavas and those of the Honolulu series. (Figure 20) It will first be noticed that the Koolau basalts show very moderate variation in silica (SiO_2) content, from 48.74 to 50.97%, despite the fact that the specimens came from localities widely scattered over the whole Koolau Range and from stratigraphically different positions. There is also a close agreement in the amounts of other oxides, except that MgO varies through a rather wide range. This close similarity in composition of the analysed specimens confirms the impression gained from petrographic study of a large number of thin sections. The Koolau rock also agrees closely in composition with the prevailing basalts of the exposed, actively building parts of Kilauea and Mauna Loa. All these appear to be the fundamental, primitive sort of volcanic rock which forms the earlier and major part of the mass of most Hawaiian volcanoes. All other varieties appear to come later in the history of any one dome and in some domes may not be produced at all.

If the Moanalua feldspathic rock should have a markedly different chemical composition from the usual Koolau flows, it would be of great interest, either as an example of abberant composition or perhaps incipient differentiation, but it is not clear from the microscopic examination of sections, that there is such a difference, the

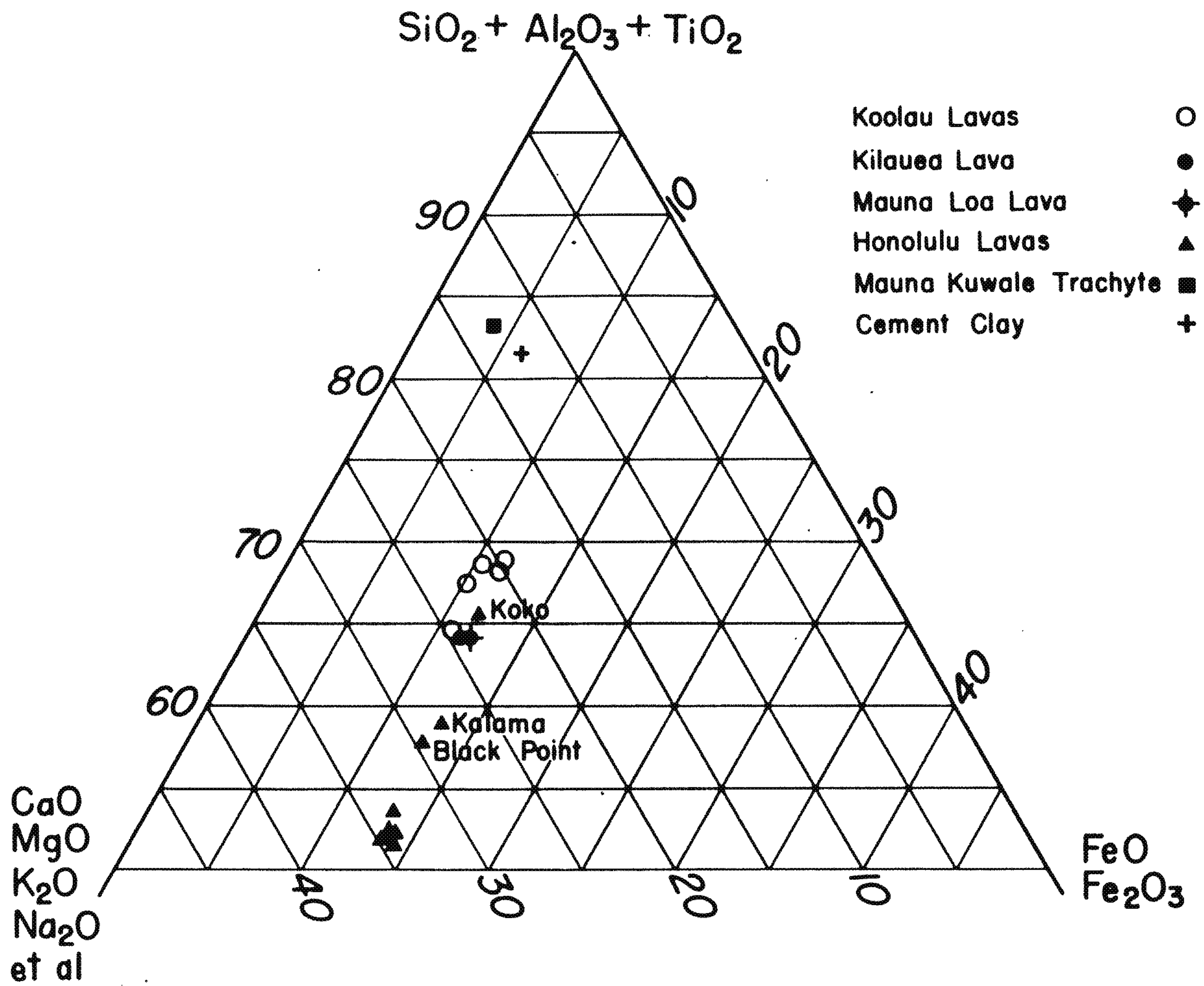

Figure 20 - Triangular diagram showing composition of Koolau and Honolulu series lava flows.

distinction more probably being one of texture and unusual growth of feldspar rather than total chemical content.

The Honolulu series lavas contain 5 to 15% less silica than the Koolau lavas do, that is from 36 to 45%, and carry proportionately larger percentages of other oxides, especially lime, iron oxides, and magnesia (with some exceptions). These are accordingly known as ultra-basic lava rocks, and the differences in content of various oxides are reflected in the differing mineral content of these rocks from the Koolau rocks. Further details on the chemical composition, mineral composition and the petrogenetic implication of the somewhat variable rocks of the Honolulu series have been presented by Winchell (1)

(1) Winchell, H., Op. Cit., 1941.

KOOLAU ASH AND TUFF BEDS

About all that can be said under this heading is that the sporadic lenses of tuff, contemporaneous and cognate and interbedded with the Koolau lava flows, which have been described in earlier reports, are extremely rare in the Moanalua-Halawa district. Prior to the commencement of this survey, the most detailed information on the geology of southeastern Oahu was that contained on the map and in the report published by the U. S. Geological Survey (2). On this map a

(2) Stearns, H. T. and Vaksvik, K. N., Geology and Ground-Water Resources of the Island of Oahu, Hawaii, Territory of Hawaii, Division of Hydrography, Bulletins I (Text) and II (Map), 1935.

considerable number of tuff beds and also of dikes and sills were shown in the Honolulu portion of the Koolau Dome leeward of the crest, especially from Nuuanu eastward. Not nearly so many dikes, sills or tuff beds were shown in the main leeward part of the Koolau dome west and north of the Honolulu area, but it was thought possible that readier access and more detailed interest in the Honolulu area might be either partly or wholly responsible for this difference in the indicated abundance of these features.

As this survey has progressed, with the first report dealing with the Palolo-Waialae area (in which dikes are certainly much the most abundant), it has become increasingly apparent that there is a real and marked variation in the concentration of both the intrusive bodies and tuff beds. Whether there is a causal relationship between the tuff beds and the intrusive bodies, such that their abundance or scarcity would be in some correlation, is not wholly clear, though according to one interpretation of the tuff beds, this would probably be the case. The various aspects and possible significance of this condition will be discussed further in another section.

One bed of red tuff is found at the level of Moanalua Stream at a point about 800 feet inland from the junction of the two main head branches. This is about 5 feet thick. A short distance farther inland is an outcrop of red tuff about 40 feet above stream level which is probably the same bed, though the horizon was not traced. These two represent the most conspicuous occurrences and practically the only ones in the area covered by this report.

KOOLAU DIKES AND SILLS

Dikes and sills are extremely few in number in the Moanalua and Halawa portions of the leeward slope. The main vent zone of the dome, now marked by the dike complex, lies a quarter to three quarters of a mile outside the limits of the heads of the two valleys, and few indications of an increase in concentration of intrusive bodies with approach to the vent zone were found, though it is probable that such increase does take place. Apparently the concentration over the whole area is so low that it is not significantly revealed under the existing conditions of exposure. (Figure 21)

The principal observation to be offered in regard to dikes and sills in this area is the fact that under similar conditions of exposure and of detailed observations, they are very much fewer in number. For a description of the general nature of the dikes and sills the reader is referred to other reports of the series.

At the time when the Palolo-Waialae report was written, the writer took the view that these dikes, mostly transverse to the trend of the dike complex itself, and found with some variations in concentration, across Waialaenui, Waiomao, Pukele, and eastern Manoa, were late dikes intruded into a system of fissures developed as accommodation joints to the elongate mass of the Koolau dome. At the same time, he took the view that the occasional red tuff beds interbedded in the Koolau series were the result of scattered phreatic explosions induced in lava flows at points away from their source vents.

As the detailed survey continued across Manoa and into Nuuanu, there was noted a decrease in the number of dikes and also an apparent concentration of red tuff beds. During his term of service as assistant in this work, Horace Winchell put forward alternate hypotheses to the effect that the subcomplex of dikes and sills in the Waialae,

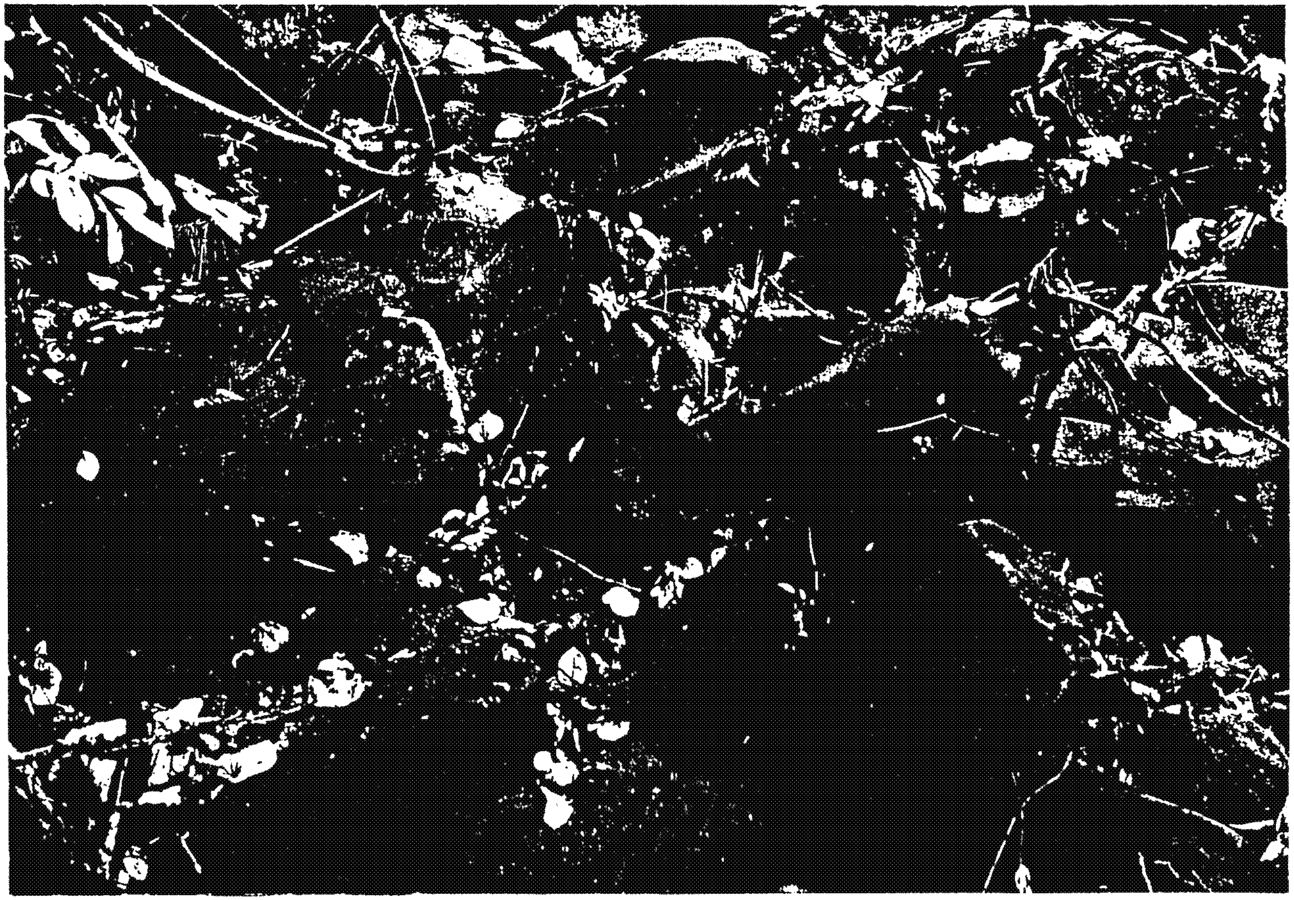

Figure 21 - Detail of outcrop of intrusive rock in chute on north wall of Moanalua Valley. Negative No. 21254.

Palolo and East Manoa band might constitute the third rift zone of the Koolau dome (recognizing the common development of three rift zones in many volcanoes, and the geometrical principle that three cracks radiating from a point are necessary to fully accommodate shrinkage in a plane) and that the red tuff beds may really be individually more widespread than they have seemed to be and are somewhat concentrated in a certain part of the section of Koolau dome and hence perhaps derived from central vent eruptions during a certain stage of the Koolau growth (1). The relation between these two hypotheses, one

(1) Winchell, H., The Honolulu Series, pp. 25-26, 124-128, 1941.

dealing with dikes and the other dealing with tuff beds, is in the bearing on the problem of former existence of a well-developed central vent and possible caldera in the upper Maunawili basin. If these hypotheses are well founded, they favor the central vent theory.

The comparative rarity of both tuff beds and dikes, except in the dike complex, in the area west of Nuuanu, as increasingly indicated by the present survey, suggests that some special condition has existed in the area adjacent to the suggested central vent east of Konahuanui, and that neither of these features can be entirely explained as due to widespread, sporadic conditions. Thus, recent findings lend some indirect support to the central vent theory.

Older sedimentary formations

OLDER ALLUVIUM

As in other parts of the Honolulu area, the categorical discrimination of sedimentary formations by age is difficult, though at a given outcrop, it is easy to distinguish between two or more alluvial or other formations obviously of great difference in age. Because of the lack of distinctive petrographic constituents, of dated, interbedded formations, and of fossils, the separation of the various formations is practically based on the degree of weathering. And because of the contrasts in rainfall, in ground-water conditions and in original permeability of the formations, the degree of weathering is often extremely variable for beds of the same age in years which are of different materials or in different locations. Hence the separation into Older Alluvium, Intermediate Alluvium, and Recent Alluvium is necessarily based on local homology and cannot be regarded as being precise in a historical sense. On the other hand, since degree of weathering is of such prime importance in the fixation of hydrologic characteristics, the distinctions here made are probably locally more useful than a strict historical classification might be, even if the latter were possible.

In the Moanalua-Halawa area, the land-derived sedimentary formations are of more than usual interest because of the conspicuous deposits which form the Fort Shafter terrace and of the interrelation between these and the Salt Lake tuffs. Without implying that it is always possible to distinguish any given outcrop or that completely valid mapping has been accomplished, certain facts have been developed.

The oldest sedimentary formation found in the area is a deeply weathered coarse gravel which lies on bedrock in various deep channel exposures and which underlies all other formations, including the gravels, tuffaceous alluvium, and the like, of the Fort Shafter terrace (Figure 22) This is here designated as the Older Alluvium. Next younger than this Older Alluvium is the Intermediate Alluvium, in which we must apparently include the whole section of the Fort Shafter terrace except the actual primary tuff layers. This Intermediate Alluvium of the seaward areas and valley bottoms is usually better sorted than the older alluvium, its gravel is fresher in most places, though in sections having a tuffaceous matrix, it may be nearly as much weathered as the Older Alluvium. The Intermediate Alluvium in the seaward area is in many places overlain by a few feet of fresh black ash or Salt Lake tuff of the latest eruption, while its own content of tuffaceous layers shows that an earlier eruption took place while the terrace was being formed. In the inland area, all the transported material on slopes, except the gravel of actual stream channels or adjacent bars, is included as Intermediate Alluvium. In the inland area, while much of the mantle rock is subject to downslope movement and wash, the deeper portions are doubtless very old, while the surface parts may represent very recent derivation from weathered bedrock. In such conditions, where weathering of the bedrock is continued in the weathering of the slowly moving detritus, the determination of the date of commencement or of emplacement becomes academic.

The Recent Alluvium includes the material of channels so obviously subject to recurrent movement and rearrangement that its freshness is evident and also includes the fresh, little-weathered

Figure 22 - Channel of Moanalua Stream near the Forest Reserve fence, showing Koolau bedrock (left foot of figure), old alluvial gravel (right foot) and recent alluvial boulders (right hand). Location No. 2680. Negative No. 12641.

and loose surface material of flood plains and gentle slopes near the coast. Here, as far as exposures permit, there is commonly sufficient stratigraphic distinctness to permit some degree of separate mapping.

The Old Alluvium, here under consideration, is probably a widely distributed formation underneath the cover of later valley-filling formations in the lower valleys and perhaps on parts of the Koolau rock basement under the coastal plain. It has been found, moreover, that where the older alluvium lies on bedrock, with little exception, the bedrock is also much weathered for some feet below its upper surface. The old alluvium has acquired its deeply weathered character in place, and it is natural that the bedrock, similar both chemically and physically, to the sedimentary cover, should also have been weathered. (Figure 23) The two together, therefore, form a relatively tight hydrologic barrier over the less weathered, more permeable Koolau rock of the aquifer. The deep weathering is a consequence of their remaining long in place where climatic conditions favor such weathering and their permanence in such places depends on either relatively low slopes, or on deep burial and flanking by thick masses of other material. The older alluvium, though exposed only in a few outcrops where streams have cut deeply, is probably generally present as a mantle over the bedrock, and under later formations, in the lower parts of all the valleys and in the bottoms of wider upper parts of the large valleys where graded spur slopes are developed and where a significant amount of aggradation took place following the period of deep valley cutting. Excellent exposures of old alluvium were shown in the various excavations for the North Halawa project, described elsewhere in this report.

The physical character of the older alluvium has been described elsewhere in this series of reports. It is only necessary to emphasize that it is highly impervious and forms a very effective barrier to the movement of water. (Figure 24) It functions in two important ways in controlling water movement. Areas where the bedrock is overlain by the alluvium (and supplementing weathered bedrock) are ineffective areas of infiltration to the bedrock aquifer, and most of the rainfall which may be absorbed into younger overlying alluvial layers is probably diverted seaward on the top of the layer of older alluvium.

The second manner in which the older alluvium influences water movement is in forming sub-sealevel barriers in valley axes, which impede lateral movement of basal water and give rise to the differences in head between adjacent isopiestic areas. The first of these influences depends chiefly on the width and length of the larger valleys; the second depends on the depth to which the valley was once cut. None of the valleys of this area are as wide, or as deep, as Kalihi, Nuuanu, Manoa or Palolo Valleys, but there is considerable contrast in their form and limiting dimensions. For example, Moanalua and the two Halawa branches are sufficiently wide at the margin of the range so that there is good reason to believe that the former valley rock profile extends 100 to 200 feet below the present flat of the lower valley and hence probably at least to basal water level. This is a minimum based on the projection of the moderate slope of the present rock walls. (Figure 25) On the other hand, if there should be rock slopes as steep as those found on the eastern side of Palolo Valley by diamond drilling, the rock floors of the two Halawa valleys somewhat inland from the nose of the spur between them could be as much as 125 feet

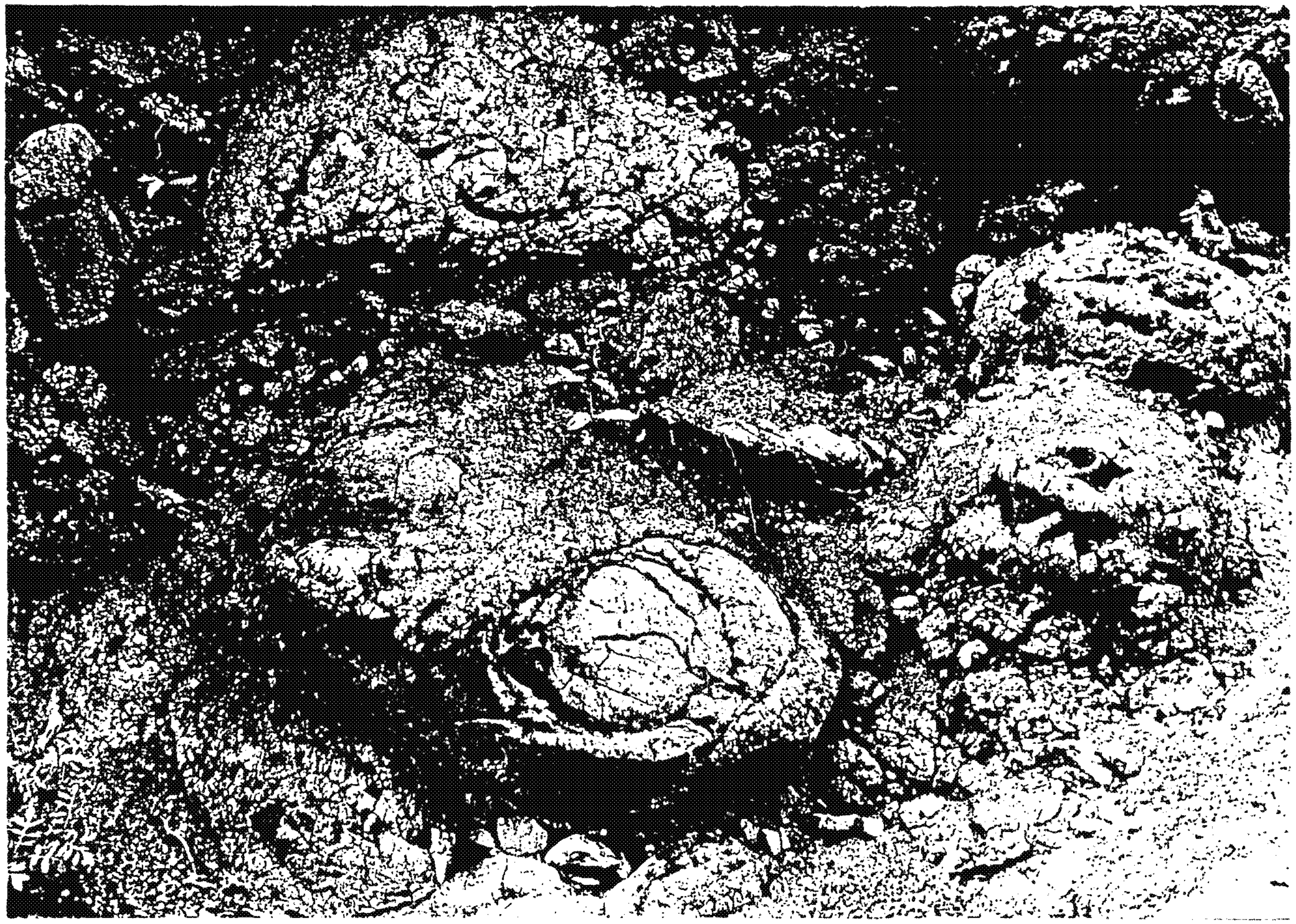

Figure 24 - Detail of older gravel showing crumbling due to secondary weathering. The generally soft condition of the boulders and the major spheroidal structures are due to the primary weathering, either in situ or before the gravel was deposited. The crumbling and fine-meshed checking shown in this picture are due to the exposure to air of material having the physical and chemical constitution developed earlier and may properly be called secondary weathering. Negative No. 21238.

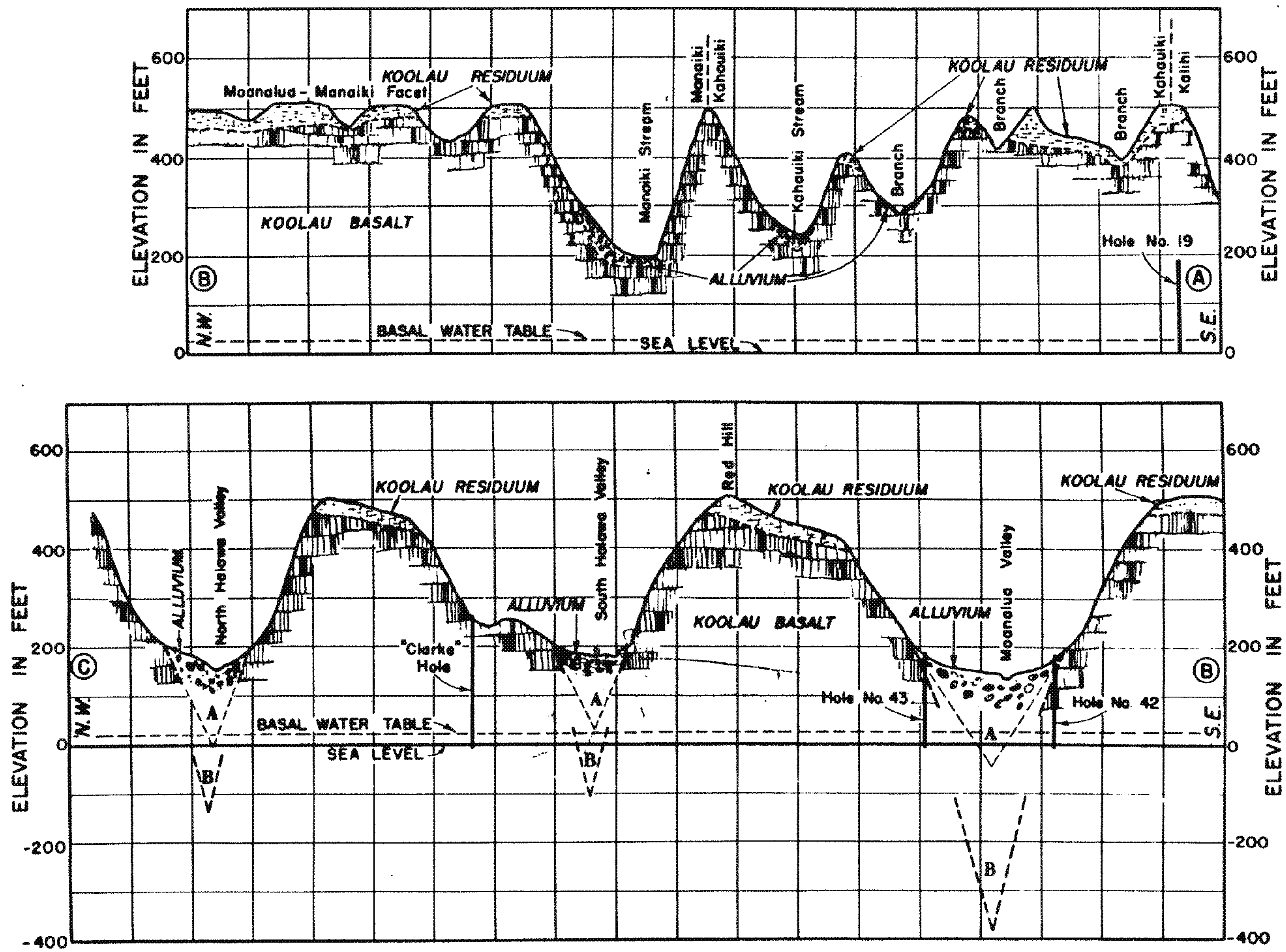

Figure 25 - Geologic cross-section from Kalihi to Aiea, along a line tangent to the several 500 foot contour loops on the spur facets. The several drill holes indicated are not on this line but each is projected into this cross-section in a position corresponding closely with its relation to the valley and the valley wall. The basal water table from Kalihi to the east side of Moanalua approximates the elevation of 24 feet (October, 1942); on the west side of Moanalua Valley is a drop of about 0.70 feet, then one to 21.7 west of South Halawa and to 19.50 west of North Halawa Valley. No drill holes have explored the deeper parts of any of these valleys and possible rock profiles A and B are based on width and steepness of valley topography. Profile A is about the shallowest that seems plausible; profile B is no deeper than is possible if rock walls continue as steep as some revealed in Palolo Valley by drilling.

below sea level and that of Moanalua Valley could be more than 300 feet below sea level. The present filling of these valleys, probably older alluvium, would operate as a barrier to basal water movement, From measurements of static level in test holes from Kalihi to Aiea, it appears that the chief barriers are in the branches of Halawa Valley.

OLDER MARINE FORMATIONS

Since the term Older Alluvium has been applied to formations underlying the complex series having a tuffaceous matrix and known as the Fort Shafter terrace formation, the designation Older Marine formations refers to reef and other deposits older than the visible Salt Lake tuff. Very little is known of such deposits except from the records of artesian wells. In the compilation of well log data made by H. A. Powers and presented in Bulletin I, Plate 20, it is shown that nearly continuous coral deposits prevail in the wells between Kalihi entrance and Pearl Harbor entrance, through the Salt Lake sector, from 200 feet below sea level to slightly above or below sea level. A similar condition is found in the Punchbowl sector of the coastal plain from Rocky Hill to Nuuanu Valley. There is abundant evidence to show that the mass of the exposed, visible tuff cones of Salt Lake and Punchbowl lies over and hence is younger than these sub-sealevel coral limestones. It seems clear that within rough limits the latter are correlatable with the older alluvium. The accumulation of the older alluvium obviously occupied a long period after the cutting of the deep valleys and perhaps several stands of the sea. The older limestones were formed during the same interval and were probably most continuously and thickly deposited in the sectors not opposite river mouths where alluviation would make conditions unfavorable for coral growth, hence, opposite stable cones. Whether this is the full explanation of the restriction of thick masses of sub-sealevel coral to the Punchbowl and Salt Lake area, or whether there was additional aid to coral growth by the earlier formation of lava flows or tuff cones around these vents is not wholly clear. At any rate no direct evidence of such early eruptions has been discovered.

Because of the method of boring the artesian wells, by churn drilling, there is little direct information on the character of coral of this formation. Below the base of this limestone, from somewhat over 200 feet to over 700 feet below sea level, the well logs reveal an alternation of chiefly gray, or sticky clay, with subordinate thicknesses of coral, the latter being from 1/3 to 1/6 of the whole thickness. There is little doubt that the whole mass is of marine deposition and represents the marine offshore fill which took place as the sea level fluctuated, probably rising intermittently from more than 1000 feet below present level. The lower part of the section, with clay predominant, probably represents the part deposited before the outlets of streams, particularly Nuuanu, Kalihi and the Pearl Harbor group, had been restricted to something like the present channels. After this restriction had taken place through growth of coral and probably a retarded aggradation, the parts of the shore line not directly in the line of valley outlets became the sites of deposition of over 200 feet of nearly pure coral.

The effectiveness of marine, as well as the subaerial parts, of these older formations as water barriers, is practically shown by the behavior of artesian wells and the general artesian condition. It is possible that if fresh, unweathered coarse rock detritus were placed in fairly deep water, offshore, that it would remain unweathered and relatively permeable. However this may be, there is no evidence that any such deposition has taken place, and every indication is to the effect that all the terrigenous marine sediments in Hawaii are sufficiently weathered before, during, and after deposition as to be of very low permeability. The calcareous marine sediments also, where these occur under a moderate cover, are not generally or notably permeable, though cavernous conditions occur locally in the zone just at sea level, owing to solution by fresh, basal water.

Honolulu volcanic series

GENERAL

This volcanic series consists of basalts, black sand and cinders, and brown and drab palagonitic tuff erupted from upward of 30 vents in southeastern Oahu, all located southeast of a line drawn due northeast from Pearl Harbor entrance (1). These rocks differ markedly in

(1) Winchell, H., The Honolulu Series, Harvard University, Thesis, pp. 1-198, 1941.

composition from the Koolau series, being, according to Winchell, linosaite, nepheline basanite, nepheline basalt, and nepheline-melilite basalt. The chief difference is in the lower percentage of SiO_2, 36.72% to 45.13% in Honolulu series, as against 48.74% to 50.97% for the behavior of artesian wells and the general artesian condition. It is possible that if fresh, unweathered coarse rock detritus were placed in fairly deep water, offshore, that it would remain unweathered and relatively permeable. However this may be, there is no evidence that any such deposition has taken place, and every indication is to the effect that all the terrigenous marine sediments in Hawaii are sufficiently weathered before, during, and after deposition as to be of very low permeability. The calcareous marine sediments also, where these occur under a moderate cover, are not generally or notably permeable, though cavernous conditions occur locally in the zone just at sea level, owing to solution by fresh, basal water.

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Rocks from four vents of the Honolulu series are present in the Moanalua-Halawa district. These are (1) Salt Lake tuff, (2) Aliamanu tuff and basalt, (3) Makalapa Tuff, and (4) the lava flow (Manaiki) and cinders from Puu Kahuauli, near the head of the Kalihi-Manaiki divide. The dating and chronology of the several eruptions is not easy to determine. It is evident to anyone examining the rocks of the region that there have been at least two periods of eruption, separated by an interval long enough for considerable erosion to have taken place and for a soil to develop and support a growth of trees and other vegetation. (Figure 29) The upper tuff layer is the principal mass of gray and drab palagonitic tuff which forms the exposed parts of the Makalapa, Aliamanu and Salt Lake craters as well as the rock surface just under the soil over large areas outside the rugged crater masses. The older tuff is in places a primary tuff, deposited directly from the air, but the more conspicuous parts of it occur as alluvial lenses and finer matrix in the gravel sections of the Fort Shafter terrace. It is not certain whether all three of the vents, Salt Lake, Aliamanu, and Makalapa, were active during two stages of activity; but this is probable, since sections which show the two tuff formations are widespread and occur near and around each of the vents. Likewise, there does not yet appear to be any entirely conclusive evidence to show the age relations of the early or the late eruptions of the several craters.

It seems reasonably certain that the Aliamanu vent was active during the early stage, which has been included with the Kaena (95-foot) and Laie (70-foot) stands of the sea by Stearns (1) He

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(1) Stearns, H. T., T. of H., Division of Hydrology, Bulletin 1, pp. 108-111, 68, 1935.

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considered that all the earlier tuff came from the Aliamanu vent. This is possibly the case, though the exposures on the east and south sides of Salt Lake Crater strongly suggest that a crater ring of similar form to the present one was in existence around the Salt Lake vent prior to the deposition of the late tuff. Though tuff from the several vents has not been discriminated petrographically, if this mass did antedate the later tuff, it would prove earlier activity of the Salt Lake vent. Though there are considerable thicknesses of the earlier tuff at various points near Makalapa vent, the earlier activity of that vent is not so readily shown. Late tuff, carrying fragments of earlier tuff, have been found in the Makalapa area, but these do not prove if the earlier tuff was of Makalapa origin or was from Aliamanu or Salt Lake vent.

A late eruption of Salt Lake is indicated by the heavy mantle of tuff around the Salt Lake rim. Stearns concluded that the late tuff came chiefly from Salt Lake and Makalapa vents and states that it can readily be distinguished from the Aliamanu (earlier) tuff by its subaerial character (1). The present writer recognizes that

(1) Op. Cit., p. 127, 1935.

substantially all the late tuff is primary, aeriform ("subaerial" can apply to stream-laid gravels and is not a precise term for what Stearns meant) tuff and that much of the earlier tuff consists of alluvial derivatives. However, he believes that some of the layers interbedded in the terrace section are primary, aeriform tuff and that more of the primary tuff is found that Stearns appeared to recognize. Hence, this character is hardly a criterion for discriminating the two tuffs. In some places the two can be separated by a soil layer, but in others there is only a slight break between what appear to be primary layers of the two.

It seems clear, because of the preservation of the shallow Makalapa Crater that here there was at least an important eruption at the late stage. As to Aliamanu, the problem is whether the tuff which lies 50 to 100 feet thick (2) on its north rim, is wholly of Salt Lake

(2) Stearns, p. 109.

origin, or is partly from Aliamanu vent. Stearns apparently took the former view, since he says, "The upper tuff can be traced to Salt Lake Crater; hence no doubt exists as to its source (3)."

(3) Op. Cit., p. 109, 1935.

Granting that this upper tuff can be traced to the mass which mantles the Salt Lake rim and which contains numerous bombs in the Salt Lake area, it is not clear why it cannot also in part have come from a simultaneous eruption of the Aliamanu vent, a possibility which Stearns does not appear to consider. In fact if this tuff is 100 feet thick on Aliamanu rim, this appears to suggest partial derivation from the Aliamanu vent, since there is sufficient indication that the thickness of this upper tuff is nowhere else of comparable thickness at equal distances from the Salt Lake vent either to the east or west of Aliamanu Crater. According to the writer's observations, the upper tuff at such distances from Salt Lake has thicknesses generally less than 25 to 30 feet, and it is doubtful if erosion has removed more than 5 or 10 feet from any parts of the surface. It is therefore regarded as more probable that the Aliamanu vent was active simultaneously with Salt Lake and Makalapa during the last stage. This has been correlated with the Waipio stand of the sea (1). No data for a more precise or valid correlation have been developed during the present survey.

(1) Op. Cit., p. 127, 1935.

The allocation of the Manaiki lava flow to the Kaena stand of the sea by Stearns is based on his identification of nepheline basalt boulders in the upper part of the Fort Shafter terrace section in the Damon Road cut, and their supposed absence from the lower part. (Figure 26) It was concluded by him that "Manaiki Stream was suddenly

Figure 26 - View of gravel section in Damon road cut. The layer of coarse gravel is the layer which Stearns believed was composed mostly of nepheline basalt boulders. Negative No. 12457.

diverted to this place by the Aliamanu (early) eruption (1)." The

(1) Op. Cit., p. 109, 1935.

writer has examined this cut and has identified the beds referred to by Stearns. Specimens were taken from various cobbles and boulders in the several beds described in his section. Microscopic examination of these does not sustain his statement that the lower boulder conglomerate lacks the nephelite-melilite basalt; on the contrary cobbles of this basalt, presumably from the Manaiki branch of the Kahuauli basalt (Kalihi basalt of Stearns) occur within 5 feet of the base of the water-laid, pumiceous "fire-fountain" tuff. Moreover, the 4-foot layer of well-rounded boulders, which he describes as consisting "mostl of nephelite-melilite basalt", and which is readily identified by the matrix of reworked vitric-lithic tuff, was closely examined and found not to carry any more nephelite-melilite basalt than adjacent beds. Chips were taken from 11 boulders at random in this bed and on thin sectioning not one was found to be Manaiki basalt. On the other hand, this type of basalt could be found by careful field selection. In short, examination of this road cut shows that this basalt occurs sparingly throughout, with a concentration comparable to that in the gravel of nearby Manaiki Stream and did not indicate any localized concentration in any particular bed (2). This means that the Kahuauli

(2) It is fair to point out that Stearns made his observations without benefit of thin sections and the microscope, but it appears that his assurance in certain generalizations was not justified.

eruption was at least as early as the Kaena stage but may have been earlier.

Whether the pumiceous, fire-fountain tuff described by Stearns and lying directly on the Koolau soil at the base of the Fort Shafter terrace, came wholly from the Kahuauli vent is not easy to determine. The thicker deposits near the mouth of Manaiki Valley may as plausibly be derived from this source as any, but the Fort Shafter terrace in various other places, as far as Halawa Valley, also carries a pumiceous cinder deposit at its base, and for these parts the Kahuauli source is less plausible, since we do not know, with certainty, whether one or more vents of the Salt Lake series were active as early as this or not. We are faced by the alternatives of assuming the Kahuauli eruption to have been very voluminous and widespread in its deposits (aided by streams), or assuming that there may have been three periods of eruption of the Salt Lake vents, as recorded by tuff beds and soils in the section referred to. The writer inclines to the latter view, having some doubt if the vent at the head of Manaiki can have produced such widespread deposits.

KAHUAULI BASALT

This basalt was erupted from the vent on the Kalihi-Manaiki divide about 1/4 mile leeward from the main Koolau crest. Remnants of a vent cone of vitric cinders cover an area of somewhat over 100 acres of the top of the ridge at this point. The lava from this vent poured into both Kalihi and Manaiki Valleys. (Figure 27) On the Kalihi side the lava is shown on the north wall as thickly strewn large black basalt blocks in a triangular area reaching to the axis of

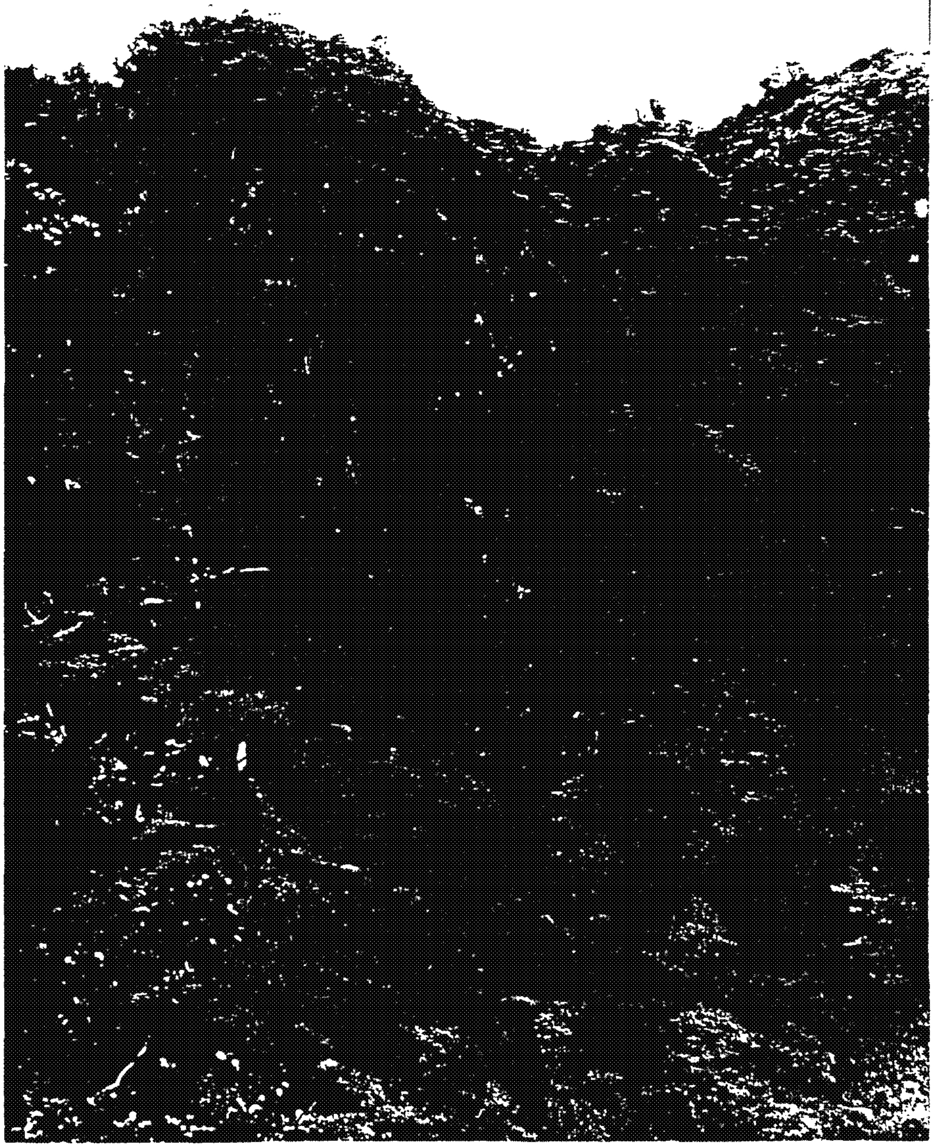

Figure 27 - Outcrop of Kahuauli basalt forming cliff on west wall of Kalihi Valley near head. Negative No. 21301.

the valley, and thence the flow is exposed at various points down the valley bottom. Evidence of the flow on the Manaiki side is confined to the black boulders which are scattered sparingly down the valley in deposits of older gravel and in the modern channel, as well as in the nearby Fort Shafter terrace. No one has succeeded in finding any of the Kahuauli basalt in place at any point in the lower part of Manaiki Valley. Moreover, it cannot be assumed that such a flow may lie in a buried valley section, since Manaiki Valley through its whole length to within a few rods of the coastal plain is at present cut down to its rock floor at many points. There is no fill at any point which appears to go more than 10 to 20 feet below the stream level. The amount of Kahuauli basalt found in the gravel of various ages is not large, but there must have been at least a few acres of the flow on the Manaiki side. There is no basis for asserting that the flow passed far down the valley, and it is difficult to estimate distance of travel by roundness of boulders. In fact the 4-foot bed of boulders in the pumiceous tuff matrix described from the Damon Road cut, "most of which are melilite-nephelite basalt" according to Stearns, is found to contain only a small fraction of Kahuauli melilite-nephelite basalt; and conclusions concerning either elapsed time or distance, based on the rounding of these boulders are subject to reconsideration (1). (Figure 26)

(1) Op. Cit., p. 105, 1935.

Megascopically, the Kahuauli lava is a dense, black basalt with columnar, or blocky jointing and displaying conspicuous solution pitting and grooving where exposed. The rock also contains large inclusions of olivine, which show various stages of weathering, as well as large pyroxene phenocrysts. The following petrographic description of the Kahuauli basalt (Kalihi) is quoted from Winchell (1).

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(1) The Honolulu Series, Thesis, Harvard University, pp. 49-54.

Kalihi. The Kalihi volcanics consist of flows of nepheline-melilite basalt and some pyroclastics. The lava member contains conspicuous olivine nodules in angular to subangular shapes, which stand out on the surface of the flow in places where chemical weathering and solution of the rock by rain water have produced lapies and similar forms (Fig. 23). I collected a number of such nodules. Most of them have about 95 per cent olivine, a little magnetite, and still less interstitial material. A few contain pyroxene and feldspar (labradorite). The contact between the (fresh) olivine grains and the surrounding nepheline-melilite basalt is generally sharp, with no evidence of reaction. In some cases a slight concentration of nepheline occurs around the olivine.

Besides the conspicuous olivine nodules, this flow contains rounded pellets of tuff which weather out, leaving holes in the surface of the flow. It also has numerous small veinlike and nodular pegmatitoid segregations. Figure 24 is a composite photomicrograph across the boundary of such a segregation. Considerable amounts of analcime and apatite are concentrated in these areas, especially in the interstitial material last to crystalize. The grain size is multiplied many times as compared with that of the major part of the flow. Large grains of nepheline, melilite, augite, and a few of olivine and magnetit occur in the pegmatitoid areas. Apatite needles several millimeters long are common in them, although apatite rarely exceeds 0.2 millimeter in length in outside areas. Estimates of the proportions of the minerals in various parts of the Kalihi flow are given in Table VI. Some remarkably large (4 mm) magnetite aggregations are found standing out in relief on surfaces of the flow near where olivine nodules appear. Unusual features observed in many places along Kalihi Stream are the large calcite crystals grown through considerable areas of the more porous parts of the rock. In thin section these areas have a "poikilitic" texture with calcite "oikocrysts" surrounding the usual rock minerals, which have slightly larger grain sizes than the main body of the rock.

Table VI

Percentage composition
of phases in Kalihi volcanics.

Minerals	Normal flow W-365	Calcitic bodies W-418	Pegmatitoid bodies W-314.1	Dunite nodules W-314.2
Olivine	15	10	10	85
Augite (zoned)	1	5		5
Melilite	20	20	20	
Pyroxene	30	10	30	
Magnetite	5	3	5	4
Nepheline	30	35	30	
Analcime	tr	1	3	
Apatite	tr	tr	2	
Hastingsite			tr	
Iddingsite	?			
Calcite		15		
Zeolite		1		
Labradorite				6

This basalt formation being in very small volume, and possibly not anywhere in place in Manaiki Valley, is of no hydrologic significance in this area. In Kalihi Valley, it is important in retaining valley-bottom water above the old alluvial cap rock which lines the valley.

SALT LAKE TUFF

In an earlier section the age relations of the tuffs of the Honolulu series in this area have been discussed. For practical purposes the tuff will be described as a unit. Within this classification is the upper tuff, mantling much of the surface in the Salt Lake area, and the thin ash mantle found on the northern part of the Fort Shafter terrace, as well as the lower lenses of tuff, including much alluvial tuff, interbedded with the Fort Shafter gravel.

In the mapping it has been only partly practicable to separate the two tuffs. The lower or earlier tuff is in some places largely alluvial, with scattered or more numerous pebbles of weathered Koolau rock included. Even in these sections, however, there are usually some layers which appear to be uniformly mantle-bedded, aeriform ash or tuff representing primary deposition. The chief occurrence of primary earlier tuff is around the shore of Pearl Harbor in road cuts from Aiea southward, in Moanalua Valley, and around Salt Lake. Near Aiea on the main highway, on the Red Hill road south of the South Halawa bridge and inland from Salt Lake, there are outcrops in which the late tuff lies with erosional unconformity on the weathered top of the earlier tuff, or on a soil developed on the tuff, or on gravel overlying the eroded tuff. (Figures 28 and 29) In some places the tuff is partly alluvial, but in others, especially along the Pearl Harbor road from Makalapa Crater southward to Puuloa Junction the early tuff seems to be a primary tuff, on which the later tuff appears to lie with very slight break. (Figure 30)

Megascopically, the primary Salt Lake tuff is a fine-grained, compact rock which is mechanically weak and breaks into irregular chunky blocks. It has only a moderate tendency to split along the stratigraphic surfaces and often fractures alternately with and across the laminae. The chief structure by which the bedding planes can be identified in a hand specimen is a rude alternation or variation in coarseness of grain due apparently to successive pulsations and cessations of deposition of the coarser fragments. (Figure 31) Commonly, neither the top nor the bottom of the coarser layers is a sharp contact

Figure - Outcrop on Puuloa Road showing latest Salt Lake tuff, top and right, overlapping truncated edges of older tuff and alluvial formations. Lowest, light-colored bed in left half of picture is coral reef. Negatives No. 21258-259-260.

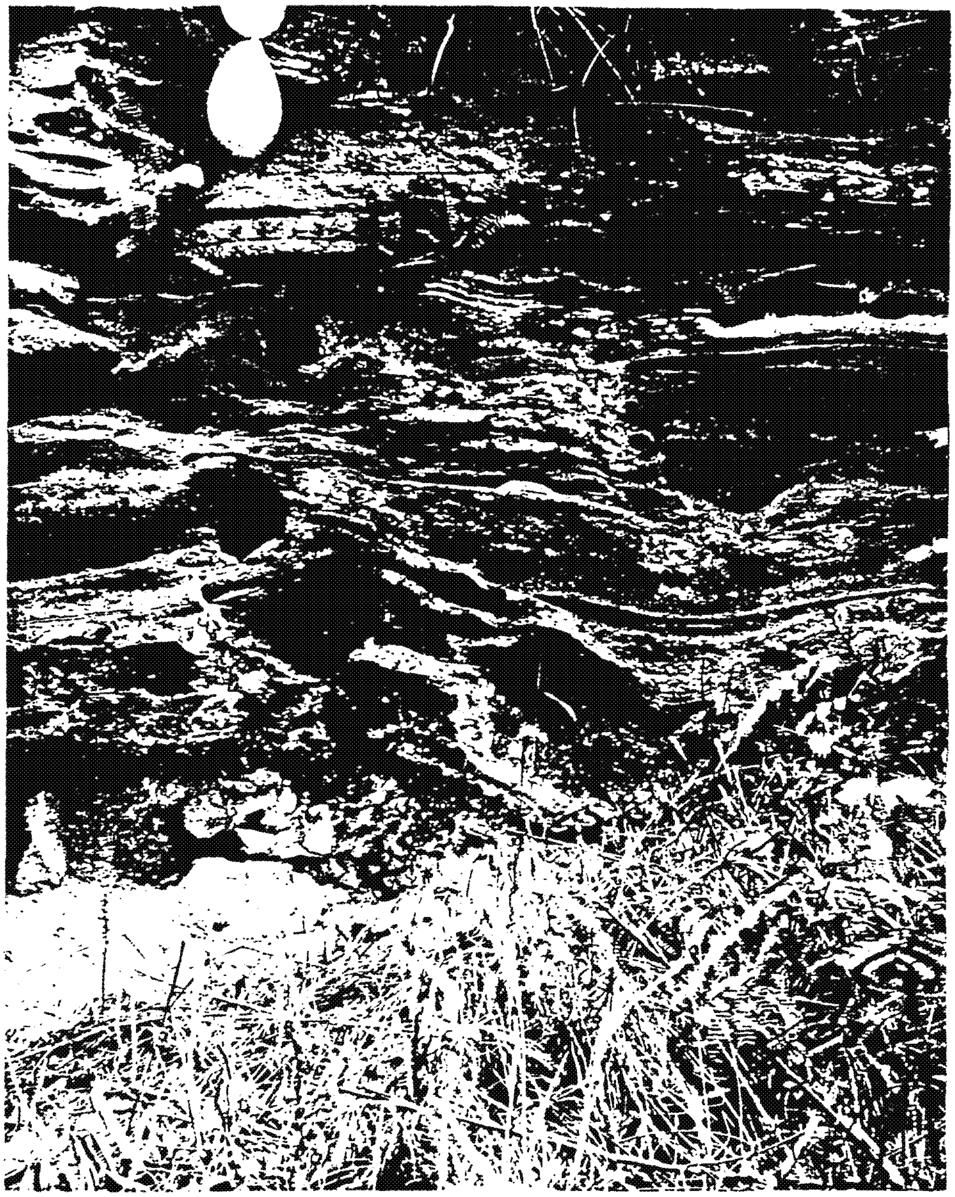

Figure 29 - Tree molds in late Salt Lake tuff, in road cut south of Halawa bridge. Such molds, open or filled by petrified wood replacements, are found in various places in the Salt Lake area and prove that the later eruptions came some hundreds or thousands of years after the earlier ones. Negative No. 21379.

Figure 30 - Contact of tuff of Salt Lake Crater on gravel which in turn lies on Koolau basalt. Road cut in Moanalua Gorge. Negative No. 12451.

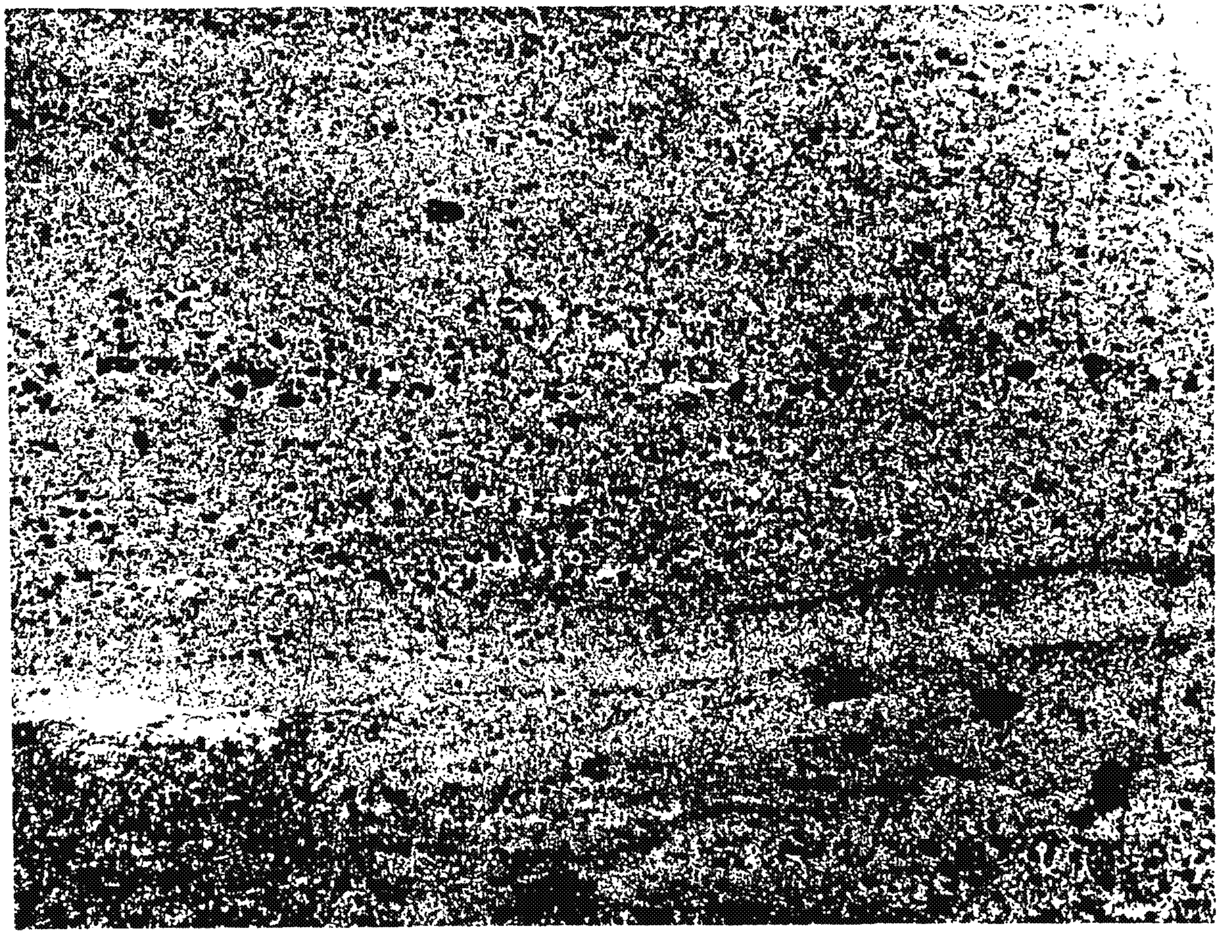

Figure 31 - Detail of broken surface of Salt Lake primary tuff in railroad cut. Determination of top and bottom in detached blocks is somewhat difficult. A slight gradation upward to finer material, from each band of coarse lapilli is the only criterion. Negative No. 21395.

the larger fragments, whether of 1/4 inch or 1 inch size, are usually partly imbedded in and partly covered by the adjacent finer material.

The coarser fragments contained in the tuff consist chiefly of Koolau basalt, in various stages of weathering and with various colors, with minor amounts of cognate basalt of the same eruption where the size is large enough to have permitted crystallization before cooling. The finer grains, chiefly below 1 millimeter, are pellets or aggregates of vesicular, palagonitized glass. The whole is indurated by compactio and in the coarser sizes the grains are conspicuously outlined and most of the interstitial space filled by secondary calcite.

In some layers there are pellets of aggregated ash, or what have been called accretionary lapilli, formed either by smaller nuclei falling through the air and adding fine dust, or by rolling down the steeper slopes and similarly adding dust. Also there are fragments of an earlier tuff, not always demonstrably of an earlier eruption and possibly in part from the same eruption. The whole mass has the structure of a gravity breccia, with no discernible imbrication or other orientation of the particles, except the rude layering as to size above mentioned.

Viewed under the binocular microscope at low powers the particle which compose the Salt Lake tuff show a remarkable variety of colors and textures, which appear to have been accentuated by the secondary mineralization and modification which probably took place while the deposit was hot and moist. By comparison it appears that the Salt Lake tuffs have much larger proportions of accidental lapilli of Koolau rock and much smaller amounts of juvenile, essential glass. Hence, there has been much less palagonitization, and the Salt Lake tuff is much less brown or ruddy in general appearance and much more gray or drab, due to the various tones shown by the weathered and altered Koolau fragments combined with the light colors of calcite and other secondary minerals (1). As seen under the microscope, nearly every

(1) Stearns, H. T., Op. Cit., pp. 108-111, 127-129, 1935.

Macdonald, G. A., T. of H., Division of Hydrography, Bulletin 5, pp. 55, 1940.

grain shows its own peculiar pattern of growth of secondary minerals and filling of vesicles.

Where exposed to the air, the primary tuff gradually reveals a system of jointing; and the surface often becomes closely checked, the rock breaking into small subspheroidal blocks or crumbs. A few feet below the surface the rock is probably essentially unaltered from the condition of induration and secondary mineralization it assumed soon after the eruption. It is believed that this induration tended to produce a sufficiently impervious mass so that subsequent weathering has been relatively much less than in the mixed, secondary tuff formation laid down under alluvial and ordinary subaerial conditions. In addition, it should be recognized that the primary tuff is considerably younger and lies in an area of relatively low rainfall.

Petrographic characteristics of the Salt Lake tuffs as seen in thin section have been described elsewhere by the writer, by Stearns, by Macdonald, and by Winchell (1). The latter has indicated that he

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(1) Wentworth, C. K., Pyroclastic Geology of Oahu, Bishop Museum Bulletin 30, pp. 64-72, 101-112, 1926.

Stearns, H. T., Op. Cit., pp. 108-111, 127-129, 1935.

Macdonald, G. A., T. of H., Division of Hydrography, Bulletin 5, pp. 55, 1940.

Winchell, Horace, The Honolulu Series, Thesis, Harvard University pp. 65-66, 93-95.

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did not find either nepheline or melilite in his specimens of tuff. This is in part due to the fact that so large a part of the tuff of these craters is composed of Koolau detritus and shows so few clear, juvenile pellets that might facilitate the identification of essential minerals. As Winchell mentions, the descriptions prepared by Pegau in the writer's 1926 paper include labradorite and perhaps other feldspars. Re-examination of the same thin sections used in 1926 shows these feldspars as present clearly enough but indicates the negligence of the writer and of Pegau in not making clear the fact that these minerals are contained in the fragments of Koolau rock which are abundant in the tuff. No clear occurrence of feldspar in the glass of juvenile pellets was noted. On the other hand, these pellets, though not abundant in this dominantly accidental, lithic tuff, do contain both melilite and nepheline, so that the tuff of the Salt Lake series is definitely of the nepheline-melilite series.

This fact is further confirmed by the identification of a lava flow of Honolulu basalt between elevations 32 feet and 1 foot above sea level in Artesian Well No. 160, drilled on the northern inner slope of Aliamanu Crater in 1941. This is a melilite-nepheline basalt as reported by G. A. Macdonald (1). It is overlain by Salt Lake tuff

(1) Macdonald, G. A., Op. Cit., pp. 55, 1940.

and underlain by old alluvium lying on Koolau basalt.

Intermediate sedimentary formations

INTERMEDIATE ALLUVIUM

As explained above, the detrital material which forms a widespread mantle over the surface of bedrock and which takes somewhat different forms in areas of contrasted rainfall, is included as intermediate alluvium when it is not clearly a part of the very early, older alluvium and not a part of the recent flood-plain or stream-channel detritus. In the valleys of the many minor side channels in the mountainous section, it is commonly the case that in the upper portion, just below the ridge crest there is a mantle rock which consists of moist soil and rock detritus which has been moved slightly by gravity from its original position. Because this material in its lower part may be fairly old and because it is compact, ill-sorted and not highly pervious, this is included in the intermediate formation.

Lower down in the side channel is commonly a section where falls and cliffs prevail and where the channel is usually cut on rock, and there may be little detrital cover even on the side slopes. (Figure 32) Still lower, where the channel has a reduced grade and meets the fringe of detrital fans, there is usually an increase in the detrital cover,

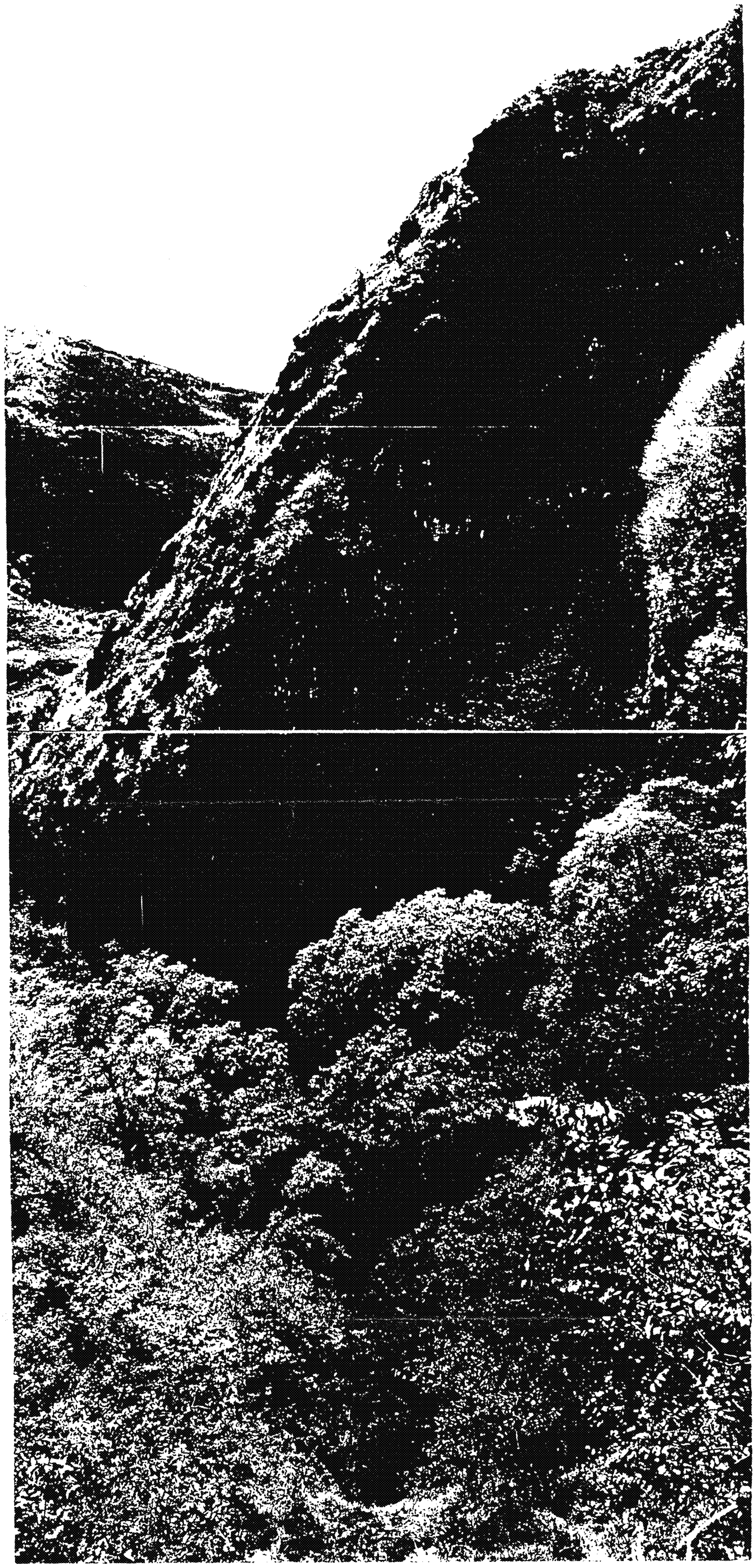

Figure 32- Vertical panorama looking down small valley and into Moanalua Valley, from the northwest side, two miles inland from the golf course. Negatives No. 21250-1-2-3.

which is better sorted than above and which often fills the channel so that no bedrock is seen until the main channel is reached. Along the middle sections of the main channels, such as Moanalua or Manaiki, the types of alluvium seen, and their alternation with bedrock follows a rather systematic pattern. The main channel usually shows a marked meandering from side to side, in a belt 200 to 500 feet wide. In the outer bank of each major bend, bedrock is commonly exposed at water level and often continues part or all the way up the valley wall. (Figure 33) As the channel swings back away from the valley wall, but continues to bear against the projecting downstream spur, there is often a continuation of bedrock outcrop for a short distance, but this is overlain by weathered gravel, which forms the upper part of the spur. In some places the bedrock is immediately overlain by typical older alluvium, and this in turn by intermediate gravel, with hard, well-rounded, distinct cobbles and a somewhat looser texture. (Figure 34) In other places, commonly on the toe of the spur, the intermediate gravel alone may be exposed.

From the nature of the outcrops, it appears that the older gravel has assumed its character under conditions which have been stable since the period of valley filling which immediately followed the period of great erosion of the Koolau Range. Naturally, the zone which has been continuously one of aggradation or of stability since that time has been that zone from 1000 feet below sea level to a few hundred feet above sea level. In the inland zone above that, erosion has to some extent continued, since in such areas the effect of a change of sea level base would not immediately and perhaps not at all become a factor in erosion.

Figure 33 - Southeastern bend of Manaiki channel, showing Koolau basalt in valley wall, and in channel, where three successive rock pools are developed by erosion of the irregular lava flows. The slope inside the bend, to the left, consists of gravel fill, of the old and intermediate series. Negative No. 12496.

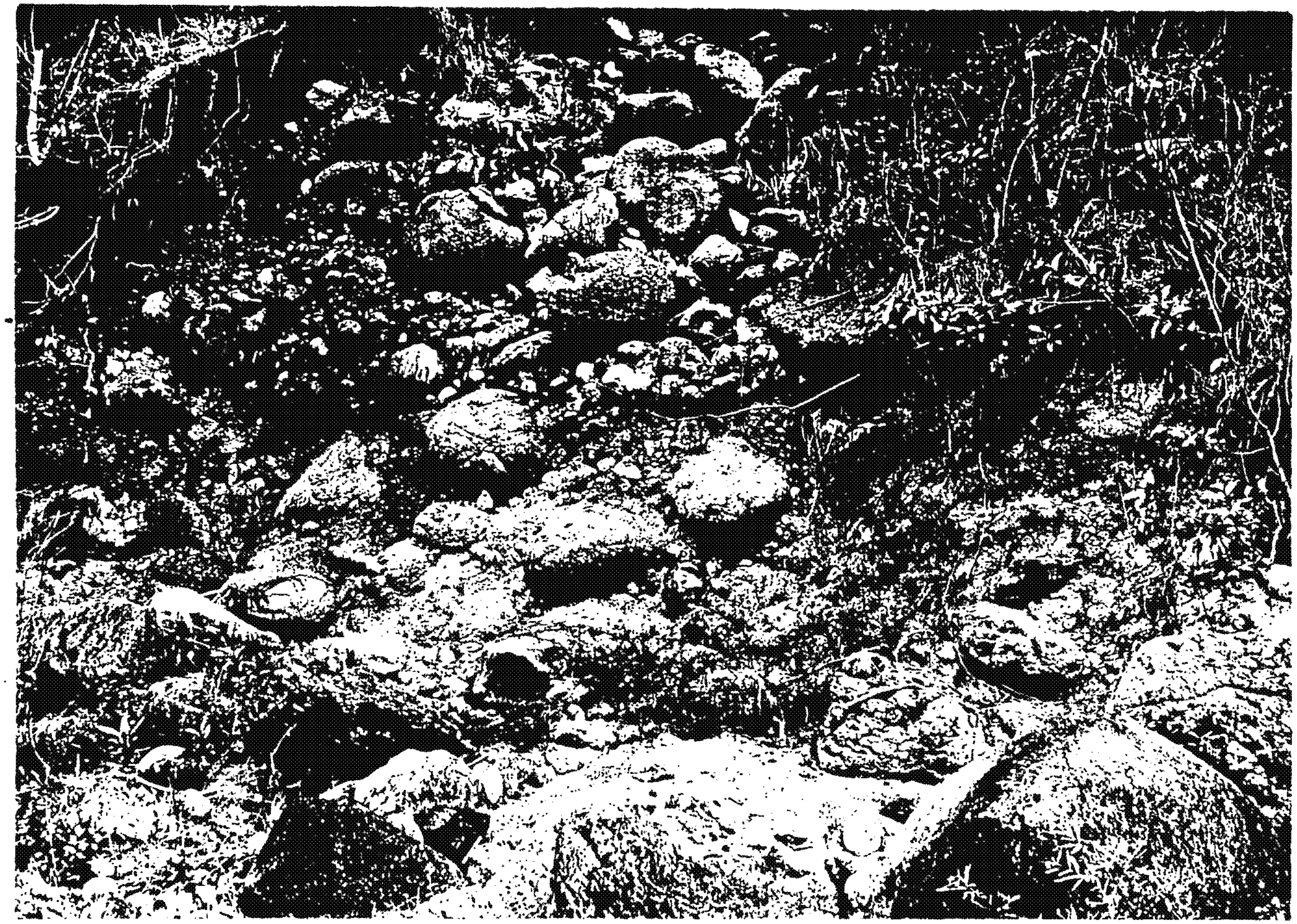

Figure 34 - Contact of younger gravel on old deeply weathered gravel. North wall of Moanalua channel below present road end. The upper gravel is composed of sound, only moderately weathered cobbles and boulders which form a moderately permeable mass. The lower gravel is weathered to a soft, tightly rammed, highly impermeable mass, in which the individual boulders are no harder than the matrix. Stream erosion cuts this gravel to a smooth surface, truncating both boulders and matrix; only subsequent exposure to air and wetting and drying action by differential ravelling outlines the boulders in relief. See Figure 24. Negative No. 21237.

Hence we do not find and would not expect to find the older gravel or alluvium lying on bedrock surfaces at 1000 or 1500 feet above present sea level. Here the detrital cover is intermediate alluvium discussed in this section. In a few places this intermediate formation is fairly strongly cemented and moderately compact, but it is still sufficiently distinct from the older alluvium in the one respect that its boulders are fairly hard and sound and protrude from an eroded outcrop and that it has not so completely expanded and rammed itself by weathering, as to produce a hydrologically tight, self-sealing mass. Locally, this formation ranges from fairly impervious in its more stabilized, geologically older parts to moderately pervious in the more mobile, steeper parts of the mantle in the mountainous. This portion includes the prevailing soil, which might be classified as recent detritus if sufficiently detailed observation were practicable.

In the channels of active streams, the loose bouldery and pebbly detritus is classified as recent alluvium and, if the surface adjacent to the channel is loose-textured, bar gravel, it may be practicable to map it as recent, though many such areas may have been overlooked. Low-level, flood-plain deposits of fine-grained alluvium have also been mapped as recent alluvium, though in many places intermediate, and probably older alluvium may lie underneath.

Good sections of the typical hillslope mantle material in the lower valleys are found in the portal excavations for the Halawa project, the main portal on the north side of North Halawa, and the transmission tunnel portals on the two sides of the inter-Halawa ridge.

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Good sections of the typical hillslope mantle material in the lower valleys are found in the portal excavations for the Halawa project, the main portal on the north side of North Halawa, and the transmission tunnel portals on the two sides of the inter-Halawa ridge.

In each of these cuts the upper parts are in dark, black or drab, soil or recent slope wash with moderate amounts of coarse blocks or boulders. At a fairly definite but irregular line, 5 to 10 feet below the surface, is the base of this material and the top of a lighter colored, more cemented gravel or taluvium, in which the boulders are moderately weathered, though many of the kernels are hard. Typically, this material grades downward without a sharp break and seems to be much more completely weathered where it lies on the weathered surface of bedrock. In general, these sites have probably been sites of continuous deposition from the commencement of formation of the older alluvium, and only scattered interruptions or changes in stratigraphy are found.

In the main portal cut, in the upper part of the bouldery alluvium, about 10 feet below the base of the drab, recent mantle rock, is a lens about 4 feet thick which is composed of red-brown cinders or ash from one of the Salt Lake explosive eruptions. Both above and below this are bouldery layers. Farther down in the section, not over 10 feet above the surface of bedrock, is another zone in which the matrix surrounding the boulders is especially rich in weathered red cinder particles. This represents an earlier eruption from one or more of the Salt Lake vents. In the country seaward from the Halawa site, the latest Salt Lake eruption is represented by a layer, 2 or 3 feet thick, of porous, laminated gray ash or tuff, and the same bed is found in the south portal to the transmission tunnel. It is not clearly demonstrable that the upper red tuff layer in the main portal cut corresponds to this layer.

The intermediate alluvium is a vastly important formation in the retention of rain water and the regulation of both runoff and infiltration to underlying and more permeable bedrock. The total amount of water stored at any one time in the mantle rock of the chief intake areas, mostly intermediate alluvium, is certainly very large, perhaps of the order of 1 to 2 feet of water, or something approximating the annual increment by infiltration. In one sense, it is unfortunate that despite its retention of this amount of water, the intermediate alluvium is neither permeable enough, nor porous enough to yield water into wells or tunnels in quantities significant for municipal use. There are many places in the mountains where a few feet of digging would yield 100 to 1000 gallons a day at most seasons of the year, enough for a small camp, but development from alluvium of quantities justifying even small pipe lines is not possible. On the other hand, the reliability of our deep basal supply is rather intimately protected by the very fact that the intermediate alluvium and the related subjacent weathered surface of bedrock is sufficiently low in permeability to prevent depleting its content of stored water by artificial development. Much as we might like at certain times and in some places to take water from this source, it is just as well that we cannot effectively do so.

THE FORT SHAFTER TERRACE FORMATION

Along the margin of the Koolau spurs west of Kalihi, under the Fort Shafter grounds and in remnants westward to Halawa Valley, a complex gravel and tuff formation has accumulated by grading to a sea level probably about 80 to 100 feet higher than at present (1). The

(1) This is the Kaena Terrace of Stearns.

tentative dating of this terrace formation rests on the grading of the terrace to one of the sea-level stands recognized by Stearns.

There is no evidence to indicate that a terrace at this height was ever built along much of the Honolulu shore, and the same is true of the western Pearl Harbor shore. It is not likely that if such terraces had been built they would have been wholly cut away; hence it appears that some special reason may have existed for the formation of such a terrace in this position. The most probable cause is the obstruction which developed off the shore between Kalihi and Aiea when the first eruptions of the Salt Lake craters took place. (Figure 35)

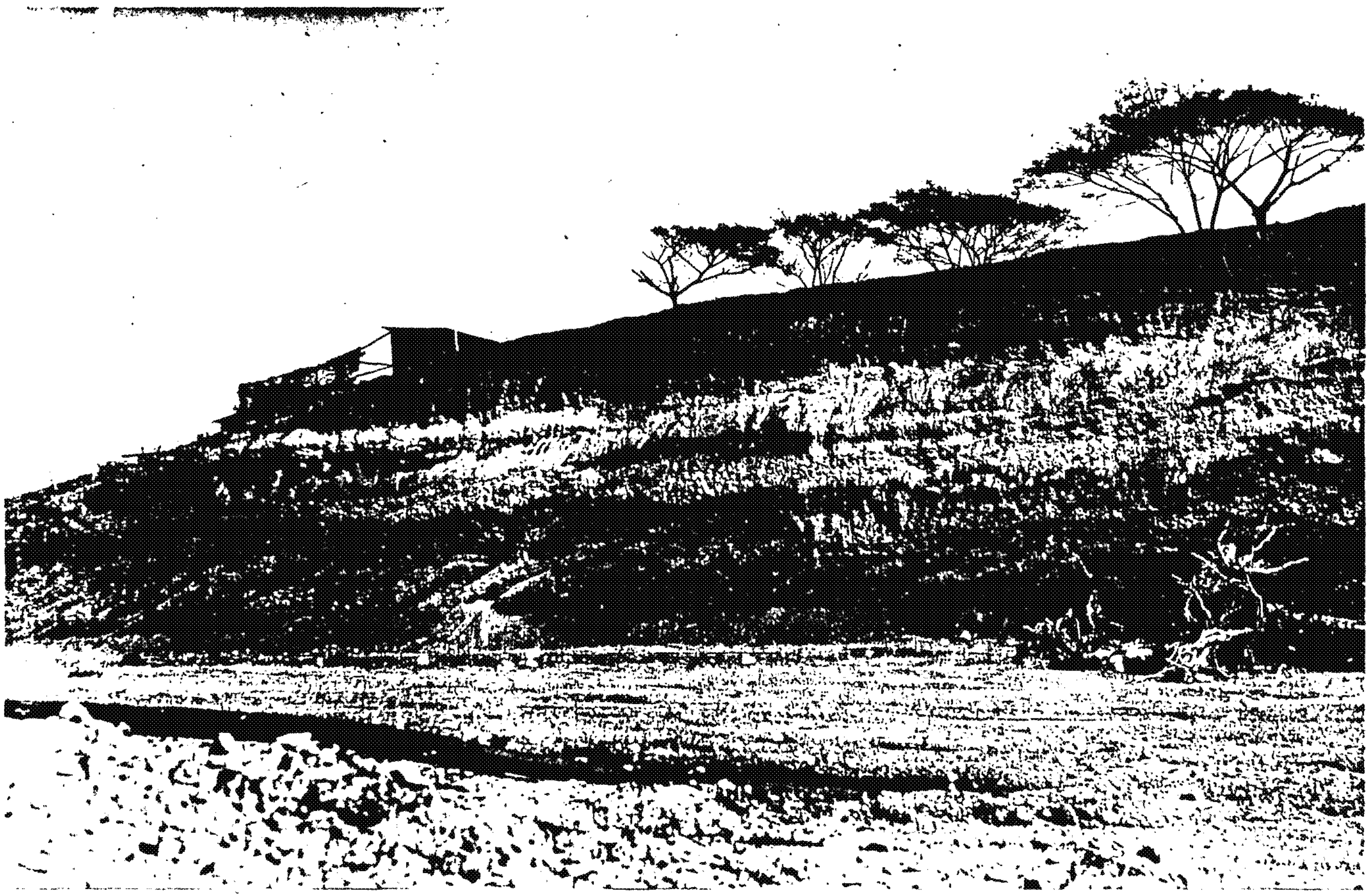

Figure 35 - Exposed section of Fort Shafter terrace formation seaward from Aiea. Negative No. 21307.

GEOLOGIC SECTION EXPOSED IN DAMON ROAD CUT

TABLE QUOTED FROM H. T. STEARNS			FINDS AND COMMENTS BY PRESENT AUTHOR
Description	Thickness (feet)	Altitude of Top of Bed (feet)	
Reddish-brown soil.	1	90	
Thin-bedded lithic Salt Lake tuff.	4	89	Possibly from Salt Lake alone, but equally likely all vents of group were active.
Fine, brown soil.	5	85	
Brown, lenticular pebbly conglomerate.	2	80	
Well-rounded boulders, most of which are melilite-nephelite basalt containing olivine segregations cemented in a matrix of reworked black vitric-lithic tuff, possibly deposited as a mud flow.	4	78	Carries scattered nepheline-melilite basalt boulders but no more abundant than lower beds. 11 samples taken at random were all Koolau basalt.
Coarse boulder conglomerate. No nepheline basalt boulders noted.	15	74	Carries scattered nepheline-melilite basalt boulders.
Brown sandy silt, possibly a soil.	.5	59	
Stratified water-laid fine pumiceous fire-fountain deposit containing a few waterworn pebbles of Koolau basalt.	10	58.5	Contains scattered nepheline-melilite basalt cobbles as low as other cobbles go.
Red residual soil.	2.5	48.5	
Weathered Koolau aa basalt.	5 +	46	
	49 +		

The presence of cobbles of the Kahuauli basalt in the lowest parts of the Fort Shafter formation indicate that this lava flow which passed down Kalihi Valley in quantity and possibly also came down Manaiki Valley was placed prior to building of the terrace. Hence, we can properly assume that considerable blocking of outlet resulted from the deposition of the apron of Kahuauli basalt at the mouth of Kalihi Valley on the east and from formation of the several members of the Salt Lake group of craters on the west. There was probably also deposition of considerable amounts of easily transported ash over large areas of the mountainous country. This ash was quickly washed off to aggrade the lower valley mouths and contribute to the terrace built in the choked, offshore bay of Manaiki and Moanalua Valleys on the east, and Halawa Valley on the west.

The lower part of the Fort Shafter formation in many areas consists largely of volcanic ash, deposited subaqueously either by streams or in the shallow sea. Higher up, the formation becomes more gravelly and carries layers of boulders up to 3 or 4 feet in diameter near the chief channels. The remnants of the terrace now preserved are also capped at the top by from a few inches to several feet of Salt Lake tuff or slightly cemented black ash of the last eruption, the thickness depending on the distance and direction from the Salt Lake vents.

Like most gravel formations close to mountainous source areas, the section of the Fort Shafter series is variable, with bouldery layers giving way irregularly to finer-grained, more largely tuffaceous layers. Some parts of this formation have been alluded to as consisting of mud flows (1). It is likely that small mud flows took place during

(1) Stearns, H. T., Op. Cit. p. 19, 105, 1935.

the period when excessive ash deposits were being eroded from inland slopes following explosive eruptions, just as occasional soil avalanches produce mud-flow deposits today, but the writer does not agree with Stearns in his apparent belief that the mud flow has been a significant agent in the transportation of large boulders (2). The particular

(2) Op. Cit., p. 105, lines 12 and 13, 1935.

"nepheline boulder conglomerate" referred to by Stearns has already been shown to be misnamed, since of samples taken at random from 11 prominent boulders, every one is of Koolau basalt and none are of Honolulu basalt. Such a conglomerate, which shows rather striking dominance of rounded and rather well-sorted boulders, does not at all justify interpretation as possibly due to mud flow, and appears to have no more and no less a proportion of Kahuauli basalt than the whole terrace series here.

The most important consequence of the building of the Fort Shafter terrace was the fixing of the present drainage pattern of streams from Kalihi to Aiea. Moanalua Stream was forced southward to join the lower course of Manaiki Stream, the several branches of Kahauiki were merged on the terrace and now reach the sea through one channel, and the two branches of Halawa were merged in the course of being forced northward by the building of the Salt Lake craters and the forming of the terrace. Thus, the waters of at least seven valleys are now merged in three outlets, Kahauiki, Moanalua, and Halawa, a process of integration which is the normal course of stream evolution, but which has been accelerated in this area.

INTERMEDIATE MARINE FORMATIONS

Considerable amounts of both pyroclastic material and gravel and silt derived from the land were deposited in the sea offshore from the Moanalua-Halawa area during the period of growth of the Fort Shafter terrace, forming a submarine extension of that terrace. Much of this debris was laid on a foundation of reef, partly below and partly above present sea level. There is considerable evidence, cited by Stearns, to show that the later Salt Lake tuff was deposited during a period of lowered sea level, known as the Waipio stage, which followed the Kaena stage when the Fort Shafter terrace was formed (1).

(1) Op. Cit., pp. 127-128, 1935.

It also appears clear that the deposits of Waimanalo time, when the sea stood about 25 feet above the present, were laid down after the latest eruption of the Salt Lake craters.

Certain of the limestone reefs are seen definitely to lie under the late Salt Lake tuff, and others are clearly later. Very little is known of these reef formations other than the data from drill holes.

At the top is usually a layer of bright or dark red, fully pulverized lateritic soil. This layer has lost all structural evidence of its derivation from lava flows and shows no vesicles, or jointing, or other structure that is a relic from the lava flows. Instead, this layer, if it has any structure at all, often has a lumpy or irregular columnar structure due to drying after being wet, or it may display small slip surfaces due to its being heaved and rearranged under the pressure of wetting or the weight of overlying beds.

In a few places where the soil has apparently been hot and dry for a long time the process of chemical change has proceeded farther, and thin caps of a material still more highly ferruginous than the soil have been produced. This material is a low grade hematite and may contain as much as 50 percent of metallic iron, whereas the residual soil generally runs from 20 to 30% iron oxides and not over about 15 to 20% metallic iron. Such deposits, however, are very limited in extent.

The layer of red, structureless residuum is from a few inches to as much as 20 or 30 feet thick. If material as completely weathered as this is thicker, in some instances a hundred or more feet, it usually displays some distinction between the several lava flows of which it is composed and in the deeper part will display vesicles and other structural relics of the flows. The layer of red residuum not uncommonly contains kernels of sound, unweathered basalt, surrounded by a few inches to several feet of progressively weathered shells in spheroidal configuration.

The next layer downward is one in which the kernels dominate with the surrounding shells making a continuous structure. This type of structure with conspicuously large kernels is more characteristic of the weathering of thick aa lava flows. The most weathered material, along the lines of the inter-kernel cracks, is commonly soft, red earthy material comparable to the surface layer. From these cracks, radially inward toward the core, and across the several shells, the color changes progressively from red to fainter pinks, grays, gray-purples, yellows, with much individual variety. The shells are sufficiently strong not to crush between the fingers but can easily be carved with a knife, and larger slabs are easily broken with the hands. Toward the core the shell slabs may become gray, moderately sound rock.

In some sorts of lava flows, the cores shell off so as to expose hard, dense, black or dark gray rock with very little weathering. In others, the kernels are somewhat more weathered on the outside and may be weathered to the center. The exact relation between the composition of the rock, its physical constitution, and the immediate local condition of moisture and weathering which causes very great variety in the course of chemical and physical weathering from flow to flow and place to place is not known and would probably prove to be very difficult to define.

In many places, probably mostly in pahoehoe flows, the lava flows do not weather to develop cores or a notable spheroidal structure but instead seem to become softened throughout to a chalky constitution which tends on close exposure to the air to break up into small blocks about one inch or less in diameter. In certain situations on the eroding edges of ridges, the bare surface shows the weathered rock intimately divided into such blocks, which are gray inside and red or pink along the joints which bound them. The detritus which ravels from such a surface is wholly composed of these chunky, subspheroidally-rounded crumbs of weathered rock. Or, the shell parts of a spheroidally weathered terrane may ravel in this way, leaving occasional spheroidal cores perched as residuals above the general surface. (Figure 36)

The important factors in the formation of a residual cover are the weathering and chemical modification, and the thick accumulation of the modified material. In situations where the weathered and expanded material falls or is eroded away as soon as it is formed, no residual formation of significance is produced. In places where the residual material is no more than 5 or 10 feet thick and is loose and free to heave, the blanket may not develop any great imperviousness. But on fairly large areas of land of not too great a slope, such as the surfaces of some of the flow-slope facets, where the residual material lies 25 to 100 or more feet thick, the larger part of it is under sufficient load so that the expansion which accompanies continued weathering produces high pressures and rams and tightens the material without greatly displacing it and thus produces an effective seal or barrier to the movement of water.

The most conspicuous and readily observed parts of the Koolau residuum are those on the several flow-slope facets. Here the higher and more continuous areas which approximate the original surface of the flows are often underlain by 20, 30, or more feet of deep, red, soil-like residuum which only toward the bottom gives way to gray

There are many intermediate conditions, and the writer does not mean to imply that there is no red soil at all inland from the facet apex.

Beneath the more completely weathered soil layer which is commonly present under the rounded tops of knobs and more commonly absent from the crests of the saddle parts of ridges, is a zone of weathered rock comparable to that below the structureless material in the facet areas. This is the fairly soft rock in place, exhibiting the characteristic structures of the lava flows, which is commonly seen in the cuttings for trails built on Oahu by the C. C. C. from 1934 to 1936. In the mountainous sections, where primitive trails mostly followed the actual crest of the narrow ridge, these recent, so-called "sidewalk" trails have been cut on a more uniform grade around the sides of the knobs and often at about the level of the lower saddles. A very large part of the total length has been cut in soft-weathered bedrock in place, having slope angles of 45° to 65°. Hence trails of 3 or 4 feet wide on the tread have a clean-cut exposure of the bedrock of 3 to 6 feet or more in height on the inside.

The nature of the weathered rock is indicated by the fact that tool marks are still visible in many places and that the trails were dug wholly without use of explosive or power tools. Only rarely have hard rock cores more than a foot in diameter been encountered and in most places the digging has not only been of the pick and shovel sort, but both the sides and tread of the trail have been neatly shaved to the desired shape. Locally, slides have destroyed short sections of the trails, but for the most part, since the trails were cut chiefly into the rock, no sliding has occurred. It is evident that had trails been cut in slopes underlain by intermediate alluvium, more normally subject to sliding, there would have been a larger proportion of destruction.

On leaving the crests of these ridges and traversing down the lateral gullies where outcrops are more abundant, it is most common to pass 100 feet or more down the slope before rock in place is seen, and often 200 feet or more before rock sound enough for thin sections is seen. Since there is some weathering from the sides, this does not mean that the sound rock lies 200 feet vertically under the crest of the ridge. It is more likely that the weathered rock forms a sort of perched cap, thicker at the top but overlapping down the sides to a point where erosion keeps pace with weathering in the channels. (Figure 37) This weathered rock presents a complete range from slightly weathered Koolau rock, through deeply weathered rock to structureless residuum. Hydrologically, much of the weathered Koolau rock should be considered as belonging to the residual formation, despite the possibility that petrographers might draw the line in some intermediate position.

The small width of the ridge cap of residuum, both in its effect on erosional removal and also in preventing the development of deep-load pressures, probably determines that these particular occurrences of residuum do not become so tightly rammed and are not as a whole so impervious as the larger facet blankets. On the other hand, since they are of smaller size they may almost as effectively divert rain water off the few flatter areas and down the steeper channels whence at least the more torrential rainfall passes down to valley-bottom areas of cap rock. Qualitatively, the ridge-top residuum plus the intermediate alluvium or taluvium of most of the steeper slopes, work together to pass a great share of the rain water more rapidly off the slopes than would be the case with bare, unweathered rock. On the other hand, both these formations retain much water and regulate stream flow for long periods after rains.

The field measurement of permeability in masses of some tens or hundreds of feet in extent has not appeared practicable; even if it were, its interpretation in terms of actual infiltration would be difficult. Elsewhere, the writer has urged in particular an inventory study in hydrology, using the small area probably tributary to the Manoa Tunnel No. 3, where at least some information can also be had concerning the water reaching the subjacent perched and restrained water body. Lacking such a study, it is impossible to make definitive numerical statements concerning the individual formations, however clear the relative hydrologic qualities may be.

EOLIAN, TALUVIAL AND COLLUVIAL FORMATIONS

Small areas of eolian silt and eolian lag crumbs up to 2- or 3-millimeter sizes can be seen on nearly all the upper flow-slope facets at eroded edges. The eolian formation is usually but a few inches, occasionally 1 to 2 feet thick, and lies on the residual soil. Limited extent and thickness, as well as position on the top of thick residuum mean that the eolian materials, while of systematic interest to the student, are of negligible hydrologic importance. These deposits are mostly adjacent to growing erosion scars, of recent and concurrent growth, which may now be somewhat larger than they formerly were and which are supposed by many to have been started by grazing, trail cutting, or some other activity connected with modern human

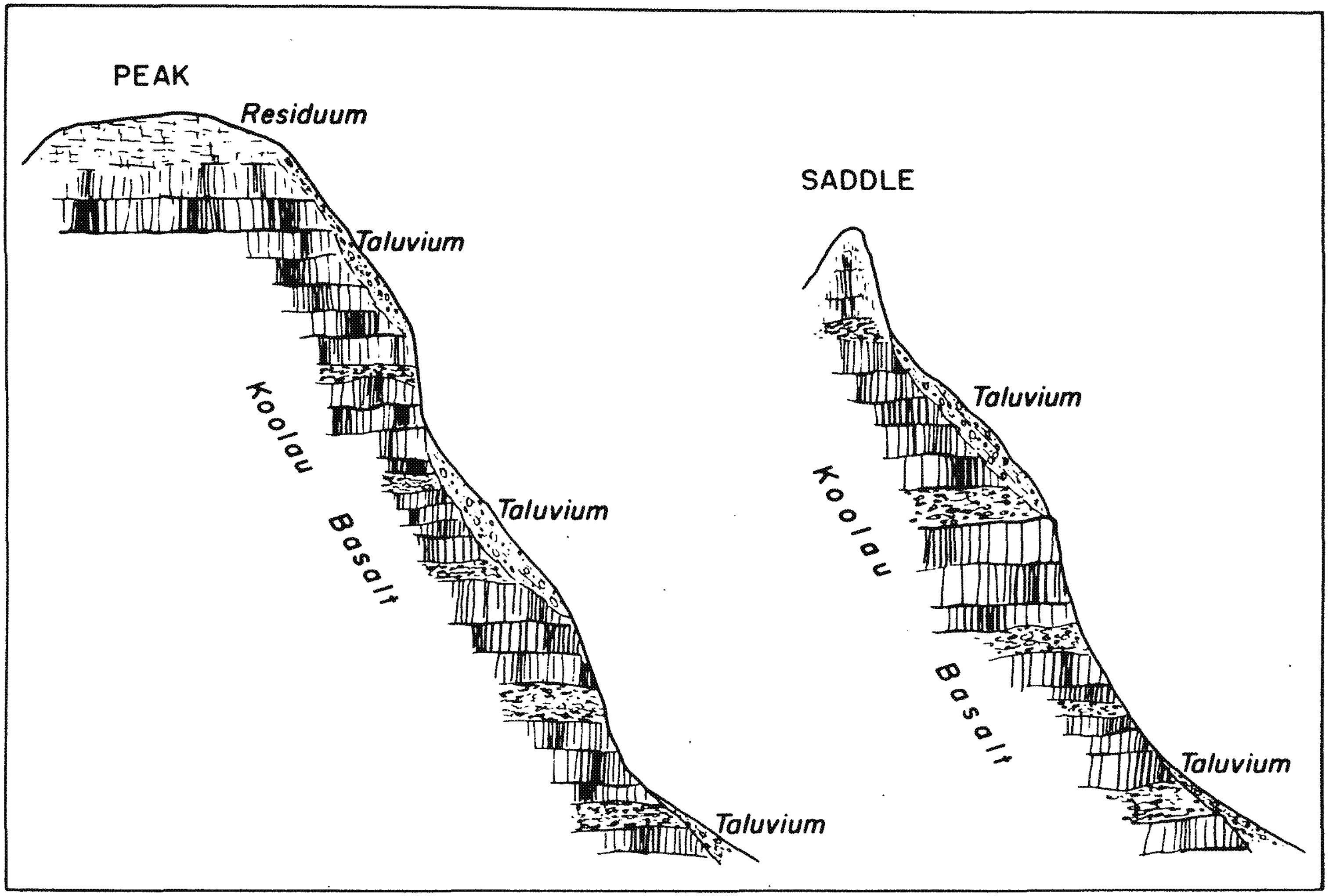

Figure 37 - Diagrammatic section showing typical inferred relation of bedrock, weathered residuum and taluvium in chutes on valley walls.

activity. The writer dissents in large measure from this view, believing that breaks in the soil cover through slides, deflation from exposed points and the like are more largely normal processes in a rugged country than is commonly recognized.

The processes of creep, sliding, colluvial transport and the like, which operate on steep slopes continue at present, and a part of the general cover of mantle rock should be included in recent sedimentary formations (Figure 38) However, in the mountainous area, separate mapping or even descrimination in section between the recent and the intermediate taluvial and colluvial materials is impracticable. Hydrologically there is no important break between them; the upper and younger parts of the mantle are more mobile and more porous and the older and lower parts less so, but no satisfactory distinction has been formulated, much less applied.

RECENT ALLUVIUM

Two types of recent alluvium have been identified in mapping this area. One of these is the channel gravel and nearby bar gravel in the lower gradient parts of the chief channels. (Figure 39) This gravel consists of loose, fairly well sorted, somewhat rounded fragments which range from pebbles of 1/4-inch size to boulders 3 or 4 feet in diameter. (Figure 40) In some places a fraction of the deposit consists of hard, unweathered basalt, especially larger boulders of dike columns and selected resistant flow basalt, and much of the rest is material from which a reasonably sound hand specimen can be taken. But in others and more generally, the larger boulders are somewhat weathered on the outside, and much of the finer material

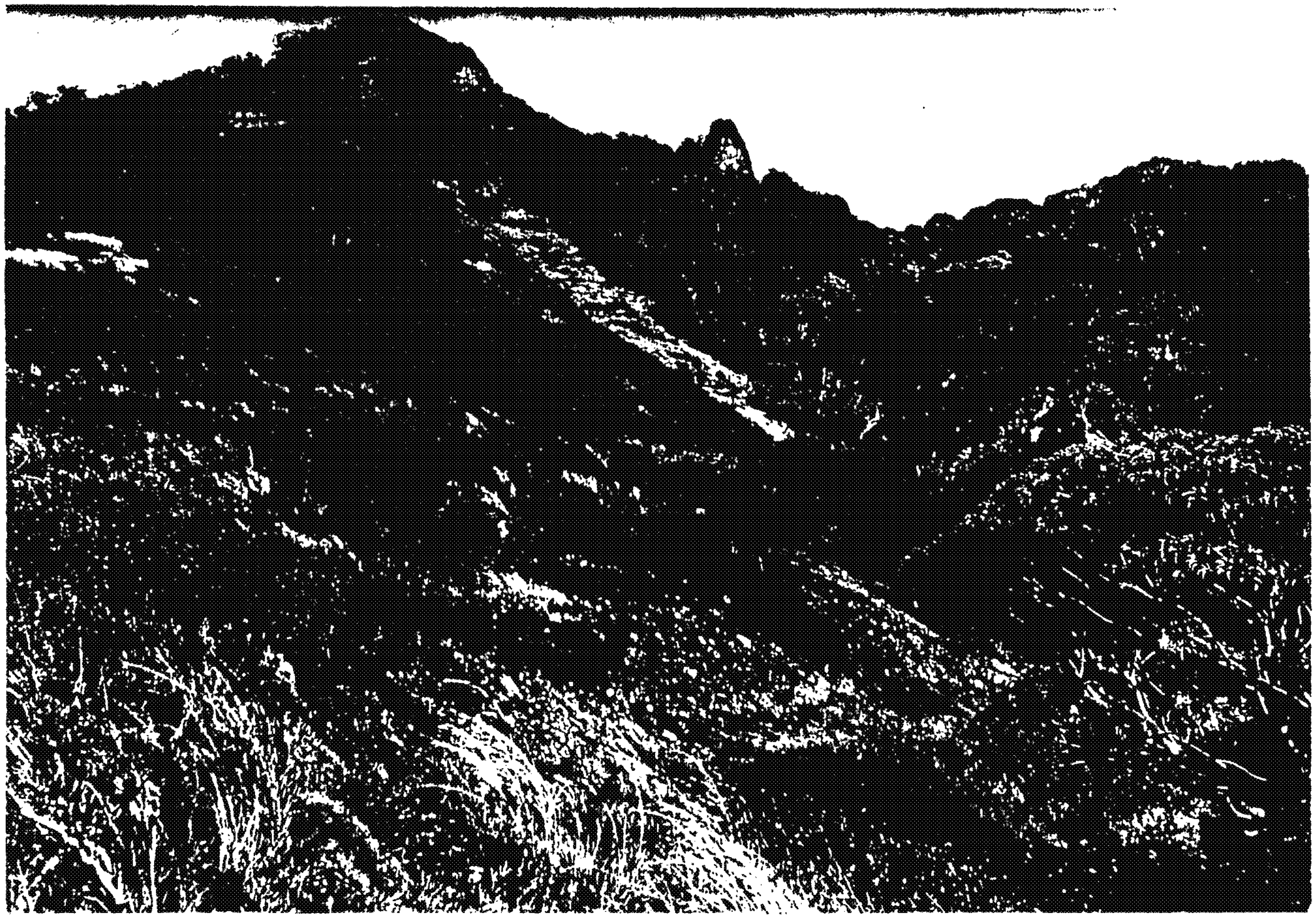

Figure 38 - Soil avalanche scars on north slopes of Moanalua Valley near head. These slips take place on slopes of 40 to 55 degrees and usually follow very heavy, local rains. They appear to be normal process by which the general steepness of slopes is maintained and determined and which is an important factor in the spread of invading types of vegetation. Negative No. 21224.

Figure 39 - Panorama of South Halawa channel. To the right is upstream. Recent gravel is in the channel and on the near bank. On the far bank, center is weathered Koolau bedrock of a spur from the north side. Old and intermediate gravel overlies the bedrock. At the left the channel reaches bedrock of the south valley wall and turns around the end of the above-mentioned spur. Negatives No. 21343-4-5-6-7.

Figure 40 - Section of recent alluvium in bank of Moanalua Stream at golf course. Negative No. 12462.

is sufficiently soft that it tends to pulverize rather than shatter under the hammer. Well-graded gravel which would give a good rattler test to highway specifications is practically non-existent in Hawaii stream channels or deposits and is rare on Hawaiian beaches. It is probable that some areas or lenses of recent gravel have been missed, but in general such materials so buried as to be obscure, are also sufficiently weathered as not to qualify under this heading.

The other type of recent alluvium is the most recent cover on low coastal or stream-bottom areas which is identified largely by its topographic situation and non-indurated character. This layer is often somewhat sharply distinguished from older rocks underneath and may lie on an eroded surface, or on the solution-etched surface of a coral reef. This material is of relatively slight importance from the standpoint of developable water supply because of its shallow character and the fact that large underground water bodies do not occur in this valley bottom relationship in Hawaii.

RECENT MARINE FORMATIONS

Formation of sediments in offshore water goes on at present as in the recent past. However, except for the shore deposits of beach sand and gravel which are seen along parts of the coast, and the very few places where a thin veneer of growing reef organisms is found, little is known of them. Studies by Edmondson and others indicate in fact that the growth of coral is relatively feeble off Hawaiian coasts today, and most reef areas show more evidence of abrasion or of mantling and burial by calcareous or land-derived detritus than of effective growth.

A far more important process at present is the modification of the coast lines and extension of artificial fill in a seaward direction in connection with various civil and military projects. It would be incorrect to imply that this process is quantitatively large by comparison to the area or volume of the island, but it involves sufficiently large areas to be significant with reference to water utilization. The combination of extensive filling of coastal flats with material making a relatively permeable mass, together with concurrent draining of such low areas, tends to produce an artificial desert terrain. Following the veneering of parts of such areas with top soil and planting of trees and grass, water for irrigation is used in considerable amounts. It is pertinent also that much of the area not planted to grass is covered by buildings and pavement and hence allows little natural ground-water recharge locally. The result is a wholly artificial hydrologic condition, the long-term result of which is not entirely clear, but is not likely to be beneficial. This pattern is true of much of the seaward margin of Honolulu and will hold in areas modified by an increasing number of civil and military projects. Detailed areal discussion of these projects is neither practicable nor desirable at this time.

DIAMOND DRILLING AND OTHER TEST HOLES

ARTESIAN WELLS

A total of 51 artesian wells has been drilled in the Moanalua-Halawa district. Some sort of log is available for only 18 of these (1).

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(1) Stearns, H. T. and Vaksvik, K. N., T. of H. Div. of Hydrography, Bulletin 4, pp. 119-131, 1938.

Stearns, H. T., T. of H., Division of Hydrography, Bull. 5, p. 55 1940.

Available hydrologic data on these wells is tabulated in another section of this report. It is unfortunate that the drilling of these artesian wells is done by churn-drill methods which do not yield at the best very satisfactory samples and also that in the majority of cases inadequate care and attention was given to making and keeping a complete record of formations penetrated. Especially in view of the misunderstanding of Hawaiian water-yielding structures by many drillers of mainland experience, as shown especially by the curiously perverse practice continuing to this day, of drilling in the middle of valleys, both drillers and owners would have profited greatly by a more systematic and intelligent approach to this problem. A number of wells in this area, particularly Nos. 193, 194, 195, 196, and 197 were drilled in valleys to depths of several hundred feet through non-yielding valley-filling cap rock, when permeable water-yielding formations were readily accessible a few score of feet to one side in the valley wall and only a few feet below the valley floor.

The chief data available from the wells for which records are available are summarized in Figure 41. These wells show that the base of the sedimentary cap rock and the top of the Koolau lava formation declines from sea level, along a line approximating the inner shore line of the several lochs of Pearl Harbor, to 750 feet below sea level along a line which passes through the tip of the Waipio Peninsula. The slope of this surface appears to range from about 250 feet to the mile to as steep as 400 feet to the mile. These values correspond too closely to the rates shown by the existing subaerial facets and the restored contours of the original dome to justify any deductions concerning modification of the original surface by erosion.

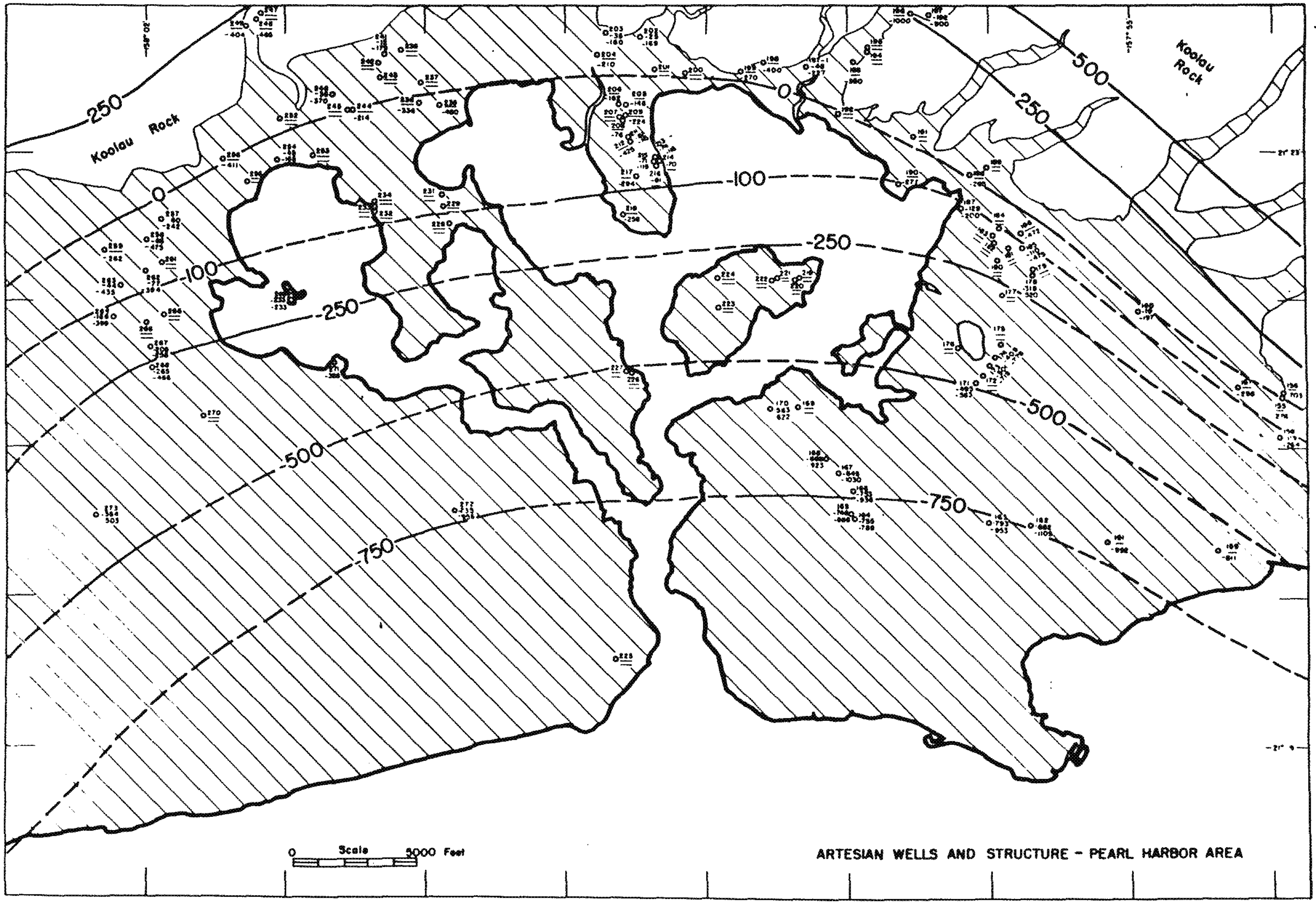

Figure 41 - Map showing locations and depths of artesian wells in the Pearl Harbor area. For each well the upper figure is the number in the new system, the middle figure is the depth measured from sea level to the top of the Koolau rock and the lower figure is the total depth below sea level. The data are summarized by the contours showing position of the surface of Koolau rock both below and above sea level. The limited data suggest a nearly uniform slope which nowhere departs greatly from 250 feet per mile except on the eastern side where the over-all slope is near 500 feet to the mile. Data are insufficient to define a cliff or bench in any particular position.

A few irregularities in the depths to Koolau rock are found, but the number of adequate records is insufficient in any one place to permit the valid contouring of cut valleys or benches, and the general envelope of submarine slopes shown by the generalized contours is all the interpretation that seems justified by the data. Moreover, while there probably were a few small canyons cut below present sea level in the mouths of some of the streams around the Pearl Harbor area, these valley flats are not at present sufficiently wide, nor of sufficient inland length to allow for deep valley cuttings comparable to those of the valleys from Kalihi eastward. From these facts and because it is obvious that in the Pearl Harbor bight, deposition has dominated over erosion, it is reasonable to conclude that no very deep valleys ever were cut in the several stream courses entering Pearl Harbor today. The problem of whether this difference in the development of the Pearl Harbor family of streams is due wholly to their convergence in the Pearl Harbor or if it may be due to differences in age of the latest lava flows has been discussed elsewhere.

TEST HOLES

Three test holes have been drilled by the Board of Water Supply in locations in or very near the Moanalua-Halawa district. Hole No. 19, drilled in April, 1935, is located not over 50 feet eastward of the Kalihi-Kahauiki boundary and was drilled wholly in Koolau rock from an elevation of 186 feet to some 77 feet below sea level. This hole was used as a test hole to indicate the character of rock and the behavior of basal water prior to the construction of the Kalihi Underground Shaft in 1936. Measurements of the basal water have recently been resumed in this hole as a datum for observation on the basal water of the Moanalua-Halawa area after the completion and commencement of water development from projects now building in this area. The cores for Hole No. 19 are preserved in this laboratory, and the log of the hole has been put on record in the Kalihi Report (1).

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(1) pp. 55-58.

Hole No. 42, located at a point about 0.95 mile inland from the Moanalua Golf Course gate on the main road, on the east side of Moanalua Valley, was drilled in 1941. This hole is near the upper edge of the valley-side talus, within 10 feet of the lowest exposed bedrock and was drilled from the elevation of 175 feet by means of a 4-inch churn drill. It is wholly in Koolau rock, and no specimens were preserved. The bottom is a few feet below sea level. Water measurements have been made twice weekly since April, 1942.

Hole No. 43 was drilled on the west side of Moanalua Valley and was completed early in August, 1942. Water table elevations are now being measured in it twice weekly, and at present are being recorded as approximately 0.75 foot lower than in Hole No. 42 on the east side of the valley.

A six-inch exploration hole, drilled by churn drill for Chester Clarke, on the west side of South Halawa Valley about a half mile east from the tip of the spur between the Halawa Valleys, has served as an indicator of the elevation of basal water in this spur. No log or samples from the hole have been studied, but it is known to be wholly in Koolau rock.

A diamond core drill hole was drilled in a small branch of Aiea Stream valley, from elevation 217 feet, at a point about 3/4 mile, N 70°E from Aiea Post Office, for Honolulu Plantation Company. This hole is wholly in Koolau basalt and was used as an exploration for the water development shaft now being excavated by that company at a point a half mile northwest in the next small valley. Water measurements have been made weekly or oftener since August, 1941, in this hole. Results of measurements in the four holes, Kalihi (No. 19), Moanalua (No. 42), Halawa and Aiea are tabulated in a following section.

A considerable footage of diamond drilling was done in the Red Hill ridge in connection with the underground fuel storage project of the U. S. Navy. Cores for a part of this drilling were turned over for preservation by this office by courtesy of the Navy, and these have been studied, chiefly to determine the proportion of aa to pahoehoe flows. The formation is wholly Koolau rock, and both the holes and the excavations themselves confirm what has previously been known about this formation.

The writer has had opportunity from time to time to see various excavations made in connection with defense projects and has profited from observations thus made possible. It is neither pertinent nor wise at this time to enumerate nor describe such excavations.

PHYSICAL PROPERTIES OF ROCK FORMATIONS

No new data on rock formations have been measured in the course of examining the Moanalua-Halawa district. General conclusions concerning the high permeability of the Koolau rock and the low permeability of the cap-rock complex and the Honolulu tuffs are supported by the behavior of water in this district. It has been apparent for many years that the artesian wells in the Pearl Harbor area have a more rapid response to wet and dry seasons and to high and low draft than is the case with the wells and basal water in the Honolulu area. This fact, coupled with the fact that about three times as much water probably moves through each mile of the Pearl Harbor shore-line zone, as passes each mile of the Honolulu shore line, indicates either greater specific permeability or shorter distances and larger exceptional openings. Since nothing in the surface outcrops or other structural features is known, which would suggest a material difference in general formational permeability between the two areas, it seems more likely that the difference in the rate of response is due to the more broken character of the cap rock and the presence of large known and probably other unknown springs in the several branches of Pearl Harbor. Various aspects of this hydraulic problem will be discussed elsewhere.

Observation of many hundreds of feet of tunnel and other excavations in the Red Hill area by various persons has led to the remark that it is strange, in view of the high rainfall of parts of Hawaii, that so little water is seen in such tunnels. It is true that in these tunnels the greater part of the walls, roof and floor is entirely dry; only rarely and locally is an occasional small seepage of water seen.

The following memorandum, prepared by the writer and quoted here, is offered as an explanation:

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Memorandum on Amounts of Percolating Water in Tunnels:

Surprise is often expressed that tunnels of various sorts driven in volcanic rocks of Hawaii above the local water table encounter such small amounts of percolating water and are often dry for long distances.

A little calculation will show why this is so. Given a district of say 100 inches of rainfall annually, with an infiltration of 25 per cent. Over the area of a tunnel section 10 feet wide and 100 feet long, the infiltrated water would amount to about 2,080 cubic feet, 15,600 gallons annually, or approximately 42 gallons a day. This would be a gallon about every 34 minutes, or a teacupful every two minutes.

A seep carrying so little water would be practically unnoticed in most rough tunnel walls, and many sections of 100 feet of tunnel carrying 50 to 100 times this amount would still seem relatively dry.

The fact, of course, is that something of the order of 1 to 5 feet of water annually is the total infiltrated water over any unit area and this amounts to not over 3/16 inch per day, and little over 0.0001 inch per minute. Obviously, such an amount of water passing through the fissured rock is inappreciable unless it is enormously concentrated in certain routes.

This general condition explains why the direct development of non-concentrated percolating water is wholly impracticable and why "wildcat" tunnels just driven into the rock at random, perhaps misled by water trickling on the surface, are generally wholly unsuccessful. In a tunnel yielding 1,000 gallons per day per foot of tunnel, the concentration is of the order of 2,000 to 1 (a common condition for good dike complex tunnels) and in a basal tunnel of 1,000 feet in length, yielding 20 M.G.D., the concentration will approximate 40,000 to 1.

Chester K. Wentworth
Senior Geologist

October 6, 1941

The several water-development projects now under construction in this area will, when brought under operation, give much additional information on the general permeability of the rock of the aquifer near sea level.

There is reason to believe that the Koolau rock of the several spurs near their seaward ends and at elevations up to 500 feet above sea level consists of somewhat thicker lava flows than the average flows in the seaward parts of the Koolau Range, a condition which in part has lead to the opening of a number of quarries in this area. These flows are thick aa flows with conspicuous clinker layers, but we have as yet no indication that the greater thickness of the flows exerts any specific influence on the hydrologic character of the mass as a whole at sea level. Experience in excavating the water development tunnel of the Red Hill project for the U. S. Navy, now in progress appears locally to modify the general statements made above. In this tunnel rock much less permeable than the usual Koolau rock has been encountered, and excavation procedures necessarily modified. It is too early to say what results will be, and no specific explanation of the low permeability of the rock can be made on the basis of available geologic data (1)..

(1) Based on a visit to the project and on conversation with B. F. Rush and H. T. Stearns.

GROUND-WATER RESOURCES

Rainfall

The rainfall of the Moanalua-Halawa district is less accurately known than that of the Honolulu area to the eastward, including Kalihi, Nuuanu, Manoa, and Palolo. This is because the Honolulu area from Palolo to Kalihi, inclusive, has been the subject of somewhat detailed rainfall measurements, not only for many years through the interest of a few old-time residents of the growing city of Honolulu, but also since the establishment of the Board of Water Supply and the initiation of various water supply investigations by Frederick Ohrt and J. F. Kunesh, shortly after 1925. At the time these studies of the Honolulu area were commenced and various raingages were set up, it was not contemplated that interests of the Board of Water Supply would soon reach outside the Honolulu district; and because of the limited growth of the city west of Kalihi, even the area of Moanalua within the Honolulu district was not included in the area of more intensive rainfall study.

As a consequence, the area west of Kalihi for some miles, though it has a number of shore zone rainfall stations and records, is even more deficient in stations in the high-level, mountainous portion than much of the rest of rural Oahu. In the valleys of South and North Halawa, Kalauao, Waimalu and Waimano, there is only one inland record, that of Station 119 of the Planning Board list, which was kept for 8 years at the elevation of 1250 feet in Waimalu Valley. This is the only record in an area of about 20 square miles and unfortunately does not permit a very accurate contouring of mean annual rainfall or an estimate of total rainfall amounts which is as accurate as is desirable. Whereas in the Honolulu area it is believed that total rainfall quantities can probably be calculated within less than 5% of the true amount, it is believed that any estimate we are able to make for the Moanalua-Halawa area may be in error by as much as 12 to 15%, owing to possible errors of as much as 20% or more in estimating the position and amount of rainfall in the zone of maximum rainfall.

As far as the records go, the rainfall of this area ranges from a minimum of less than 20 inches along the outer shore of the Puuloa area to a maximum of possibly as high as 180 inches on the northwestern margin of the district about a mile leeward of the crest of the range. It is fairly well established that the mean annual rainfall reaches nearly 40 inches along the margin of the range spurs and thence increases somewhat regularly to upward of 150 inches within the next 3 miles. Neither in this district nor elsewhere on Oahu have gages been closely enough spaced to show a systematic difference between ridge top and valley bottom or side at any given distance from the range margin or crest, though it is probable that there are such differences.

From the general findings in the Honolulu area, based on a number of raingages on the crest of the range, as well as in the leeward slope, it is evident that the mean annual rainfall is reduced rapidly from the maximum toward the crest. (Figure 42) In this area, from the generalized contouring permitted by the few stations, the amount at the crest may be as low as 130 inches, though we can have little confidence in this estimate to closer than perhaps 30 inches.

In order to lay the basis for future estimates which will be more accurate than we can offer here, two new raingages have been established in upper Halawa basin, one on a ridge and one in a valley bottom as described below.

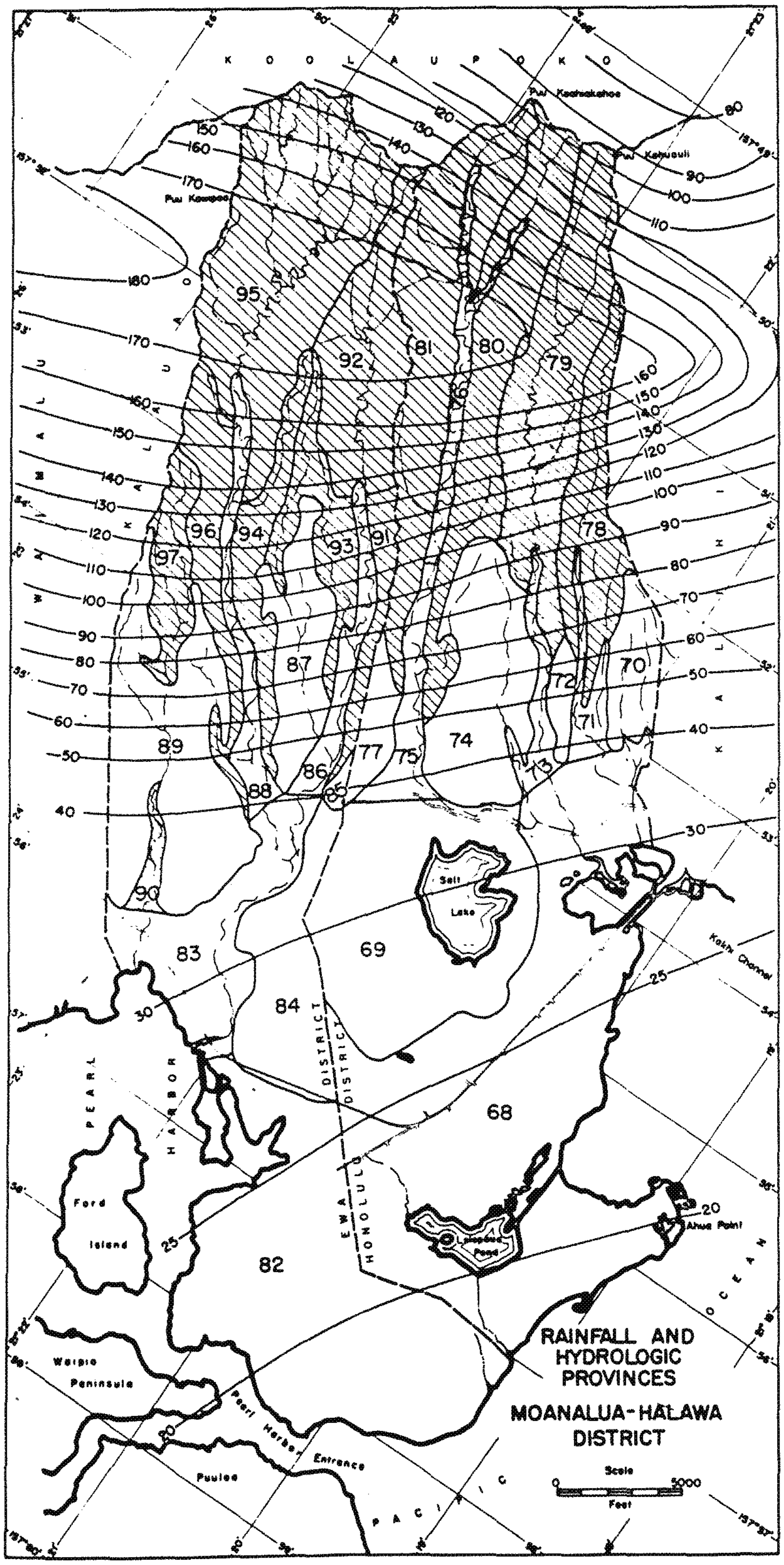

Figure 42 - Isohyetal Map of Moanalua-Halawa District, showing hydrologic provinces. (Tables, pp. 96-98, this report.) The shaded portion indicates the maximum area from which infiltration is believed to effectively reach basal water. Rainfall data from U. S. Weather Bureau, via Territorial Planning Board, 1939 and 1940.

Memorandum on Raingages in Halawa: (June 6, 1942)

Two new raingages have been installed by the Board of Water Supply, Division of Geology, in the mauka portion of Halawa, in an effort to supply data on rainfall in the higher watershed area between Kalihi and Kipapa.

The gages are of the variety where 1" of rainfall shows ½" in the container and will record up to 48" of rain in units of 0.2", or estimation to 0.1". They will be read approximately once a month for the present.

The first, to be known as Puu Kaiwipoo, is located on the ridgecrest between North Halawa and Kalauao, about 500 feet southwest of the named peak Kaiwipoo, on a slight shoulder at 2225 feet. This point is about 3700 feet southwest of the nearest part of the Koolau Range crest, which here has elevations of 2400 to 2800 feet. The position is North latitude 21-25-10 and West longitude 157-51-31.

The second, to be known as North Halawa-Upper, is located on a spur within an intrenched bend of the north fork of North Halawa Stream at an elevation of 870 feet. It is 300 feet northwest of the spot elevation "902" shown on U.S.G.S. photolithographs, 3200 feet SSW from station Puu Kaiwipoo (above), and 6700 feet west of the nearest point of the Koolau crest. The position is North latitude 21-24-37, and West longitude 157-51-42.

These two stations;have been located to meet, as far as possible, the following conditions: (a) to approximate a mile leeward of the Koolau crest in the probable belt of maximum rainfall, (b) to be one on a ridge and one in a valley, for comparison, and (c) to be so located that a route can be found by which both can be visited by an observer on the same one-day circuit.

Chester K. Wentworth
Senior Geologist

It is understood that a raingage will also be installed by the Bureau of Rural Water Supply at the tunnel portal in Haiku Valley less than a half mile from the range crest on the windward slope. Because of the deep indentation formed by the head of Haiku Valley, this is an especially favorable spot for such a gage, and knowledge of total amounts of rainfall in upper Moanalua and Halawa will be enormously improved when several years of record are available from the three stations mentioned.

ANALYSIS OF RAINFALL, HYDROLOGIC AREAS, AND WATER QUANTITIES

Moanalua-Halawa District

I	II	III	IV	V	VI	VII	VIII	IX
ydrologic Unit Areas (1)	Area (Square Miles)	Average Annual Rainfall (Inches)	Total Annual Rainfall (Square-Mile-Inches)	Mountain Rainfall (M.G.D.)	Cap-Rock Rainfall (M.G.D.)	District Totals (M.G.D.)	Isopiestic Totals (M.G.D.)	Valleys and Isopiestic Areas
) Moanalua Coastal Plain	5.64	24"	135.4		6.44			
) Salt Lake Crater Group	2.61	33"	86.3		4.11			
) Kahauiki Facet Area	0.42	59"	24.8		1.18			
) Kahauiki Valley Bottom	0.20	54"	11.0		0.52			
) Kahauiki-Manaiki Facet	0.15	54"	8.9		0.42			
) Manaiki Valley Bottom	0.24	56"	13.1		0.63			
) Manaiki-Moanalua Facet	1.22	64"	77.8		3.70			
) Moanalua Valley Bottom, Makai	0.38	60"	22.9		1.09			
) Moanalua Valley Bottom, Mauka	0.33	148"	48.7		2.32			
) Red Hill Facet	0.27	57"	15.2		0.71			
NALUA CAP ROCK AREA ALIHI DIVIDE TO RED HILL	10.26	43"	444.1		21.12			
						21.12		MOANALUA CAP-ROCK AREA (To Red Hill)

[(1) These unit areas are tracts of similar overburden and bedrock conditions from which the infiltration is presumed to go either to the basal water or to the ocean directly. They are also divided as to drainage basin and isopiestic area, and their outlines are shown on Figure 67 of the Palolo-Waialae Report, Figure 38 of the Manoa-Makiki Report, Figure 29 of this report and maps prepared in the division of geology for the Nuuanu and Moanalua districts. Outlines are based on the geologic survey, areas have been planimetered and mean rainfall computed for each of the areas by inspection of the isohyets as shown on Figure 29.]

I	II	III	IV	V	VI	VII	VIII	IX
78) Kahauiki Valley Walls	0.82	108"	88.2	4.20				
79) Manaiki Valley Walls	1.63	140"	227.5	10.83				
30) East Moanalua Wall	1.44	147"	212.0	10.09				
31) West Moanalua Wall	1.69	149"	252.3	12.01				
UNTAIN AREA, KALIHI DIVIDE TO RED HILL	5.58	140"	780.0	37.13				
						37.13		MOANALUA MOUNTAIN AREA (To Red Hill)
							(Total) 70.91	MOANALUA ISOPIESTIC ARE NO. 4 (To Red Hill)
32) Halawa Coastal Plain	3.62	22"	79.6		3.79			
33) Halawa Lower Valley Bottom	1.16	32"	37.1		1.77			
34) Western Crater Area	1.03	30"	30.9		1.47			
35) Red Hill Facet, West	0.05	40"	2.0		0.10			
36) South Halawa Bottom	0.36	80"	28.8		1.37			
37) Inter-Halawa Facet	0.72	83"	59.7		2.84			
38) North Halawa Bottom	0.42	94"	39.5		1.88			
39) Aiea Facet	1.89	55"	103.9		4.94			
0) Aiea Valley Bottom	0.12	38"	4.6		0.22			
LAWA CAP-ROCK AREA RED HILL TO AIEA BAY	9.37	41"	386.1		18.38			
						39.50		MOANALUA-HALAWA CAP-ROCK AREA KALIHI DIVIDE TO AIEA BAY

I	II	III	IV	V	VI	VII	VIII	IX
(91) South Wall, South Halawa	0.30	92"	27.6	1.31				
(92) Head, South Halawa	1.13	166"	187.5	8.93				
(93) North Wall, South Halawa	0.59	121"	71.4	3.40				
(94) South Wall, North Halawa	0.56	118"	65.1	3.10				
(95) Head, North Halawa	2.47	166"	410.0	19.52				
(96) North Wall, North Halawa	0.67	116"	77.7	3.70				
(97) Head, Aiea Valley	0.45	112"	50.4	2.40				
HALAWA MOUNTAIN AREA RED HILL TO SOUTH KALAUAO DIVIDE	6.17	144"	889.7	42.36				
						79.49		MOANALUA-HALAWA MOUNTAIN AREA, KALIHI DIVIDE TO AIEA BAY
							83.61	MOANALUA (NO. 4) ISOPIESTIC AREA KALIHI BARRIER TO SOUT HALAWA AXIS
						60.74		HALAWA DISTRICT RED HILL TO AIEA BAY

TABLE OF ESTIMATED WATER QUANTITIES BY VALLEY
HALVES AND CORRESPONDING ISOPIESTIC AREAS

I	II	III	IV	V	VI	VII	VIII
Hydrologic Components	West Kalihi Kalihi Barrier to Kalihi-Kahauiki Divide	Moanalua District Kalihi-Kahauiki Divide to Red Hill	South Halawa Subdistrict Red Hill to South Halawa Barrier	Moanalua (No.4) Artesian Area, Kalihi Barrier to South Halawa Barrier	North Halawa Subdistrict, South Halawa Barrier to Aiea Bay	Halawa District Red Hill to Aiea Bay	Moanalua-Halawa District Totals, Kalihi-Kahauiki Divide to Aiea Bay
Mountain Area (Square Miles)	1.29	5.58	.87	7.73	5.30	6.17	11.75
Total Rainfall (M.G.D.)	12.66	58.25	12.70	83.61	48.02	60.74	118.99
Rainfall on Cap Rock and Other Areas not Tributary to Basal Water	5.65	21.12	6.92	33.69	11.44	18.38	39.50
Mountain Rainfall	7.01	37.13	5.78	49.92	36.58	42.36	79.49
Runoff, U.S.G.S.		2.65			6.62		
Runoff, Estimated Total from Mountain Area (a)	1.70	2.80	1.70		8.30	10.00	12.80

(a) Runoff for each of the component areas has been estimated conservatively by comparison of areas and postulated rates with the partial areas represented by the two gage stations of Moanalua and North Halawa. Except for the allowance of an area and a discharge for South Halawa Stream of half that of North Halawa, the totals are not substantially greater than the actual gaged amounts. To reduce the amount, one can find no basis; its increase only aggravates the shortage of infiltration apparent for nearly all areas so far examined.

I	II	III	IV	V	VI	VII	VIII
Evaporation, 20% of Mountain Rainfall (b)	1.40	7.43	1.16	9.88	7.32	8.47	15.90
Transpiration (b)	1.84	7.99	1.24	11.04	7.58	8.82	16.81
Total Losses	4.94	18.22	4.10		23.20	27.29	45.51
Infiltration Remainder	2.07	18.91	1.68		13.38	15.07	33.98
Computed Basal Intake				22.66	13.38		
Known Artesian Basal Discharge (1941)				7.76	26.86		

(b) No new or more valid basis for computing evaporation and transpiration is known, though the conditions of measurement are such that no great specific accuracy can be claimed for the estimates given, as computed by the procedure used by Kunesh in 1929.

Runoff

There are two records of runoff from the area comprised in this report, a record of 15 complete years for Moanalua Stream and one for three complete years for North Halawa Stream (1). The

(1) Territorial Planning Board, Surface Water Resources of the Territory of Hawaii, pp. 17, 105, 1939.

Moanalua Station, at elevation 339, at a point about 2.5 miles inland from the margin of the range, shows an average discharge of 2.65 M.G.D. from a drainage area of 3.2 square miles, or 0.83 M.G.D. per square mile. The average rainfall is found by calculation from the hydrologic provinces to be about 145 inches. The Halawa Station is in the north branch, at 300 feet above sea level and about 2 miles inland. It shows for the short period of 3.85 years (1929 to 1933) an average discharge of 6.62 M.G.D. from 3.6 square miles of drainage area, or 1.84 M.G.D. per square mile. The rainfall in this area averages about 155 inches. The contrast between the rate of 0.83 M.G.D./Sq. Mi. for Moanalua and 1.84 for North Halawa seems to rest chiefly on a low rate for Moanalua, since the major streams of the Honolulu area, Palolo to Kalihi, average 1.96 M.G.D. per square mile, and Kalihi has a rate of 1.93 M.G.D. (2).

(2) Wentworth, C. K., Kalihi Report, p. 68, 1941.

Consideration of the rainfall records for the period 1929-1933 does not indicate that the total was far from normal, so that the

Halawa record is probably a fair average. The reason for the general low runoff rate for the Moanalua basin is not known, since each of the contrasts in topography and geology and rainfall by which Moanalua differs from Kalihi is still further shown by North Halawa in contrast to Moanalua, yet the latter valley is again comparable to Kalihi in its runoff rate.

Principles of Ground-Water Occurrence and Movement

In previous reports of this series, the writer has set forth his current understanding of ground-water behavior in the rocks of this section of Hawaii. Two chief problems emerge as the most important in the hydrology of the region, and study of each district adds some further data toward their solution. First of these problems is the evaluation of the various inland terranes with reference to infiltration and the estimation of amounts of infiltration from various sections. This problem is chiefly tied up with the gross permeability of the mantle rock in the mountainous area and with the locally deep and progressive weathering of the bedrock beneath the mantle rock, with its resulting decrease in permeability.

The rates of evaporation and transpiration are intimately involved, but their determination, while not easy, does not conjure for the geologist so complex and baffling a fabric of regional and topographic facts for clarification. It is obvious that if the entire land surface consisted of exposed, fresh lava flow rock, comparable to some terranes on Hawaii or to the floors and sides of larger quarries, or to the rock in high-yielding tunnels, the runoff would be extremely small in amount; the evaporation and transpiration would be smaller than the existing rate; and the infiltration would be large, perhaps 70 or 80 percent of the rainfall. On the other hand, if the surface were uniformly steep and fully covered by thick, compact mantle rock of the sort common in Hawaii, with no eroded breaks, it is clear that evaporation and transpiration through plant growth would be similar to what we have now, runoff would be much greater and infiltration would be small in amount, probably 10 percent or less. The gross existing condition lies between these extremes. Facet areas and valley-bottom areas are believed to approach the last-stated condition. Much of the mountainous area is probably somewhat intermediate; large areas of effective mantle rock cover retard immediate infiltration and aid runoff. But, on the other hand, some channel-bottom erosion exposes permeable and fissured bedrock, which facilitates infiltration from the immediate runoff water; and much of the mountain mantle rock, while not highly permeable, is sufficiently porous to absorb large amounts of water of which a fraction passes through and reaches basal water.

The other problem is that of the hydrologic functioning of the basal water, a vast reservoir the size, continuity and ordered behavior of which is so indubitably shown by our numerous wells, test holes and shafts. The chief elements of this problem are the rate of increment to this system by infiltration, the amount of hydraulically connected storage in the system, the total constant of permeability of the connection of the supposed bottom storage, the positions and rates of loss through the cap rock by springs and other natural leaks, and the mechanism and quantitative behavior of movement of fresh water from the bottom storage to the ocean. The general problem of bottom storage has been discussed elsewhere (1). Its quantitative application has

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(1) Wentworth, C. K., Kalihi Report, Appendix II, pp. 109-137.
--------- - - Storage Consequences of the Ghyben-Herzberg Theory, American Geophysical Union, Transactions, 1942, (In press).

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not proved practicable in any unit of the Honolulu basal artesian system, and each unit in some measure differs from the others. This is particularly true as the Pearl Harbor area is considered, since, as will be set forth in detail elsewhere, the basal water system of the Pearl Harbor area shows lower basal heads, but probably much higher rates of total movement through the system (estimated about 3 times as much per mile of shoreline) and much more rapid and sensitive response to increases and decreases in rainfall and the reverse in draft. These three characteristics are wholly consistent with each other and indicate a hydraulic system of a more dominantly dynamic, rather than static, character. The Honolulu system could be likened to a high pail, kept nearly full by moderate inflow operating against loss from small leaks; the Pearl Harbor system is a lower pail, with numerous larger leaks, kept at a level only slightly lower than that of the other by a much more copious inflow. Naturally the latter pail would show more sensitive and marked head responses to fluctuations in inflow and draft.

This much of difference we can recognize as qualitatively true; the determination of quantitative characteristics will require more data and more detailed understanding. It is pertinent to note, in approaching this study that the difference in hydrologic behavior is accompanied by and probably is closely related to the contrasted physiographic development of the Pearl Harbor area, with sea water lochs or arms reaching to contact with Koolau rock, as compared to the narrower but more continuous coastal plain of the Honolulu area.

Another point which requires noting with reference to the problem of isopiestic areas and bottom storage, is that while the static heads of contiguous isopiestic areas appear to owe their distinctness to the interposed barrier represented by the impervious cap-rock fill in intervening, deep-cut valleys, the valley-bottom fills do not extend deep enough to offer complete impediment to hydraulic interchange between the bottom-storage portions of two areas of differing isopiestic head. We should therefore expect a far less sharp contrast between the bottom heads (or depth to the diffusion zones) of two such adjacent areas, and at depths of 1000 to 1500 feet the hydraulic vector at a given point should include components not only from (1) stream tubes reaching the overlying or adjacent free basal water table and (2) the offlying free ocean surface, but also (3) the free basal water table of adjacent isopiestic areas at distances only slightly greater than (1) and probably much less than (2). Hence the behavior of the diffusion zone below the basal water table of a given isopiestic area would probably not only be governed by a lagging response to the changing heads in that area but also by somewhat weaker responses to the behavior of the basal water table in adjacent areas insofar as these are sufficiently connected as to transmit pressure effects. Recognition of this further complication may not be taken as an encouraging note, but there is no gain in ignoring its reality.

Occurrence of Ground-Water Bodies

SURFICIAL GROUND WATER

No special conditions were noted in the Moanalua-Halawa area relating to surficial ground water. Larger areas of mountainous country in higher average rainfall only served to accentuate the writer's impression of the large volumetric importance of the mantle rock and weathered surficial bedrock in holding up surficial ground water in this part of the world. It is this impression which led the writer in the Manoa Report and subsequently to introduce the term "Surficial Ground Water" and accord to this water a consideration separate from the percolating water. While this surficial water cannot be developed in significant quantities, the same can also be said of the percolating water; both are of fundamental importance in any consideration of the hydrologic cycle or in any discussion of local geologic structures in relation to that cycle, and to ultimate water supplies.

VAGRANT PERCOLATING WATER

In South Halawa Valley, at a point about 500 feet inland from the 750-foot contour crossing (Long. 157° 52' W) on the northwest bank about 2 feet above the stream, is a tunnel driven in weathered Koolau aa clinker. According to Stearns it was driven in 1900, has two branches, and comprises a total length of over 1000 feet and in 1932, was observed to be yielding about 15,000 gallons daily. When visited by the writer in April, 1923, it was estimated to be discharging at least 70,000 gallons daily. Whichever yield is the more usual is immaterial; even the latter is an amount incommensurate with the cost of driving this tunnel (1). The water developed in this tunnel is

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(1) Stearns, H. T., Op. Cit., 1935.

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probably largely retained on or in this weathered lava flow and might be classified with some justification either as surficial water, or perched water, though in part derived from percolating water.

A similar tunnel was driven in 1901, in the north wall of North Halawa Valley, about 900 feet inland from the 650-foot contour. It has two branches, one of which is reported as 2000 feet long and the other as shorter. The yield in August 1932, was reported by Stearns as about 30,000 gallons daily. The writer's estimate in 1942, was at least 144,000 gallons daily (2). It is not clearly observable what

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(2) Stearns, H. T., Op. Cit., 1935.

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structure is responsible for the flow, and it does not appear that any particular geologic condition determined the location. The water is quite as likely surficial water as perched water and is not sufficient in amount to well justify the expense of development and especially that of delivery to a point of application, a project not known ever to have been planned or attempted.

There are numerous places in the inland channels of most established streams where seepage water can be seen; digging in favorable relationship to the structure at such points may yield small amounts of water. This fact is only a natural counterpart to the existence of a perennial or nearly perennial stream. But unless specific perching or confinement of ground water occurs, such water developed is only derived from the surficial water contained in the mantle or weathered ground water and is likely to be very small in amount proportionate to the excavation required to get it. Such projects, while they might be of great temporary convenience for camps or construction project supply are not of significant value for modern municipal or plantation purposes.

PERCHED AND RESTRAINED WATER

Perched water in this part of Hawaii is always associated with intrusive sills, red tuff beds, or soil layers. All these structures are scarce in Moanalua and apparently still more so in Halawa. It is probable that certain lava flows, as elsewhere, are to a moderate extent less permeable than others and may locally perch small amounts of water; but no important evidence of perched water was seen, and conditions for its occurrence are generally unfavorable.

Restrained or confined water usually is trapped by dikes and, in some parts of the dike complex of the Koolau Range, is found in large amounts. As outlined by Stearns in 1935, however, the dike complex does not cross the head of Halawa or Moanalua Valleys and is confined to a belt fairly low down on the windward slope of the range.

This fact and the very limited occurrence of scattered dikes in the Halawa section explains the very slight indication of restrained water in the mountainous sections of this district.

FREE BASAL WATER

Direct information on free basal water in the Moanalua-Halawa area has been growing very rapidly in recent years, and a number of projects are under way, which will yield much additional information. Prior to 1930, knowledge of free basal water in this area was confined to head and overflow data on the Pearl Harbor springs and inference from the various artesian wells drilled in the covered part of the common aquifer. About 1936, the Navy drilled a diamond core drill test hole at a point on the road which climbs the Aiea spur about 1200 feet inland from the main highway at Aiea School. This hole verified the presence of free basal water, with a head of about 20 feet, and indicated the character of the Koolau lava flows at this point. A water-development shaft was dug, and water from this pumping station has been used by the Navy since 1937.

Hole No. 19, drilled by this office in the spur west of Kalihi Valley on the grounds of the then Kapiolani Girls' Home, in 1936, has made possible measurements on the head of free basal water in the eastern margin of the Moanalua, or No. 4 Isopiestic Area, since that time. Since June 1937, the Kalihi Underground Pumping Station has been in operation and likewise has yielded a valuable record of this water body. Two or three years ago, a test hole was drilled for Honolulu Plantation Company in the gulch 3/4 mile, N 70° E from the Aiea Post

Office. Late in 1941, a vertical shaft was commenced at a point farther north in Aiea Stream valley, and basal water was reached in 1942. Water will be delivered from this shaft for use by the Plantation. A test hole drilled for the Clarke Quarry Company in the northwest wall of South Halawa Valley and holes drilled in the southeast and northwest walls of Moanalua Valley for the Board of Water Supply have also yielded data on the basal water, as tabulated below.

A vertical shaft from the fuel storage tunnels in Red Hill spur has been driven to basal water and will be the basis of a pumping station operated by the Navy. This office has commenced the construction of a basal underground pumping station in the north wall of Halawa Valley. All told, there have been dug in a decade at least eleven excavations, including five shafts, one deep well, and five test holes, which reach basal water and yield far more direct and immediate information on the behavior of free basal water than was available in 1930. Some of these will be described in greater detail.

The area from Kalihi Valley barrier to and including Red Hill has been considered to be one isopiestic area for many years, since the artesian areas were first discriminated. This conclusion was reached on the basis of the heads shown in artesian wells. In 1935, when Bulletin 1, on the Geology and Ground-Water Resources of Oahu was published, the Pearl Harbor area was designated as Area No. 6, though it was recognized that there was much more variation between the heads shown by different wells in the Pearl Harbor area than was true of the typical isopiestic areas of the Honolulu area (1). Such

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(1) Stearns, H. T., and Vaksvik, K. N., Op. Cit., pp. 257-267, 1935.

differences of head in wells can be the result of leaks or of special underground conditions, and it is desirable that data on the free basal water level be compiled to check the form of this water table and to determine with greater validity than is possible with artesian well heads what subdivision into unit isopiestic areas is possible. This is not yet practicable for most of the Pearl Harbor area, but the nine measuring points mentioned will be of material aid in gathering data to interpret the relationship between the Moanalua Area (No. 4) and the eastern edge of the Pearl Harbor Area (No. 6).

At present, head data are available only from the four test holes and from the Navy Halawa shaft at Aiea School. These data are summarized in the following table.

BASAL WATER LEVELS, KALIHI TO AIEA

	Kalihi Underground Shaft (3)	Kalihi Hole No. 19	Moanalua Hole 42 (4)	South Halawa "Clarke" Hole	Navy Shaft	Aiea "Austin" Hole
Period 8/1/41 to 6/30/42						
Maximum	24.65			23.00	20.95	21.28
Mean	24.05	(1)	(2)	22.08	19.39	19.98
Minimum	23.15			20.73	17.80	18.53
Period 3/1/42 to 6/30/42						
Maximum	24.60	24.99	24.92	22.71	20.95	20.79
Mean	24.31	24.62(1)	24.56	22.18	19.59	20.13
Minimum	23.93	24.33	24.18	21.67	18.00	19.45

(1) Data not complete.

(2) Hole not drilled.

(3) Data taken from charts on occasional short period shut-down. Not comparable to static levels from Hole 19, nor so valid as the latter.

(4) Hole No. 43, on the west side of Moanalua Valley, was finished in August, 1942. During September, 1942, water levels in it averaged 0.7 foot below those in Hole No. 42.

As far as they go, and lacking contrary data, the water levels from Hole 19 and the Moanalua hole indicate a well-established isopiestic area, with a difference between the two holes of approximately 0.1 foot and with only about 0.7-foot fluctuation during the past four months.

The basal water level shown in the "Clarke" hole in South Halawa Valley is about 2.2 feet lower than the Moanalua level and shows somewhat greater variation in response to weather and discharge conditions. The Aiea hole reveals a water level averaging about 2 feet below the Halawa hole and shows still more variation in response to weather and discharge. These measurements suggest a continuous slope downward from the Moanalua hole at a rate of about 2 feet to the mile equally much as they suggest an abrupt step downward, and it is still not clear if there is a sharp hydraulic barrier, in Moanalua Valley, or South or North Halawa Valleys, any or all. Data from the Red Hill project and from the North Halawa project will perhaps give a more definite answer to this question.

The measurements so far made also suggest a transition from the more static behavior of the basal water of the Honolulu area to the more dynamic behavior of the basal water of the Pearl Harbor area, as mentioned above. Discussion of quantities of basal water will be deferred until the artesian component has been described.

The well-known Pearl Harbor Springs are fed from the basal water of the Pearl Harbor sector and have been studied and measured in some detail by Kunesh and his assistants (1). These springs are a very

(1) Kunesh, J. F., Report Honolulu Sewer and Water Commission 1929, Part IV, pp. 116-124.

large, if not an all-controlling, factor in the hydrologic behavior of the basal and artesian water of the Pearl Harbor area, but since the easternmost of these springs is Kalauao Spring, located on the west side of Kalauao Valley and about a mile distant from the nearest boundary of the Moanalua-Halawa district, it is probable that it is not an important element of the hydrology of this district as such. This is still another reason why the district in question can be regarded as transitional between the Honolulu area and the typical part of the Pearl Harbor area. The detailed discussion of the Pearl Harbor Springs will be included in reports on the central and western parts of the Pearl Harbor area.

Basal Water Projects

KALIHI BASAL SHAFT

This shaft was one of the first two basal underground stations to be constructed by the Board of Water Supply. It was constructed in 1936, and has been in continuous operation since that time. During the past year, this station has been maintained on a 24-hour daily pumping schedule at a rate of 6.2 M.G.D., with a drawdown of about 0.75 feet. This shaft is within the limits of basal area No. 4, and hence comes under discussion only briefly at this point. A more complete statement, with consideration of water quantities was included in the Kalihi Report (1).

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(1) Wentworth, C. K., Op. Cit., pp. 79-81, 66-67, 1941.

FORT SHAFTER BASAL WELL

This well, to be equipped with deep well pump, was drilled in 1942, as an auxiliary major supply source for the Fort Shafter post.

It was drilled through the roof of the refrigeration storage tunnel. Basal water in the well has a static level essentially identical with that at Kalihi Shaft, Hole 19, and with the artesian head of Well No. 146, which furnishes the main operating supply for the post. The well, drilled wholly in Koolau rock, has a diameter of 12 inches in the aquifer and was drilled to 28 feet below sea level. It is to be equipped with a pump having a capacity of 1.44 M.G.D. Present intention is to operate this plant only to furnish a small supplementary supply.

RED HILL BASAL WATER SHAFT

This basal water station consists of a vertical shaft in Koolau rock driven from one of the tunnels of the Navy Underground Fuel Storage project to sea level. The shaft revealed a basal water level essentially the same as that in Moanalua Hole No. 42. The installed pump capacity of the station is to be 20 M.G.D., but prospective needs in the near future are much less than this. Only future operations can determine what the ultimate increment yield of this station will be, and this value will of course be largely subject to coordination with the various other shafts and wells drawing from the same water supply. At present writing, despite several hundred feet of tunnel below basal water level, the excavation shows only a small yield (1). No satis-

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(1) October 5, 1941.

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factory geologic explanation of the relative water tightness of the rock has been found (2).

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(2) H. T. Stearns, U.S.G.S., is adviser in geologic matters.

NORTH HALAWA BASAL WATER SHAFT

This project with a total cost upward of a million dollars, was planned in 1941, and was awarded a Federal grant of $441,000 under the Lanham Act. Since May, 1942, it has been under construction. On June 29, the open cut for the portal had been excavated, and tunneling on the inclined shaft had just commenced. The level of basal water was reached on September 21, and at present writing (October 5) the pump room is in course of excavation.

The project consists of an inclined shaft 30 degrees, driven from the elevation of 165 feet, into the north wall of North Halawa Valley about 5000 feet inland from the main highway. At the bottom of the shaft is to be tunneling at water level to a currently planned length of 400 feet. Included in the project is 17,000 feet of 42-inch pipe line to deliver the water from the tunnel to the city distribution system. The pipe line will pass through two tunnels, one in the spur between the Halawa valleys and the other under Red Hill, where the pipe line will have an emergency interconnection with the Navy Yard pipe line from the Red Hill Basal Water Shaft. The main portal structure is located at a point where the surface of the ground was at an elevation approximating 190 feet, and at a distance of about 80 feet horizontally distant from the lowest rock outcrop at about 220 feet. No borings were made to bedrock so that the exact position of bedrock and the amount of tunneling on the incline in consolidated old alluvium before the bedrock is reached was a matter of estimate from the known position and slope of bedrock at the outcrop. Rock was actually encountered at about 12 feet down the incline.

The general appearance of the open cut for this project is shown in Figures 43 to 45. The section of mantle rock exposed includes 3 to 10 feet of recent, black or dark drab soil and subsoil at the top. The base of this layer is irregular, and beneath it is a thick mass of well-indurated taluvium or gravel and talus which contains blocks and boulders up to 10 feet in diameter and which is generally composed of cobbles and boulders from a few inches to two or three feet in diameter imbedded in a red or brown matrix of weathered finer material. The boulders in the upper part are weathered somewhat on the outer parts, but many of them have hard cores and are not easily cut by the shovel. On the other hand, in the cut as a whole, the steam shovel makes continuous tooth marks, and only a few of the boulders project from the outcrop after such excavation. The matrix is more indurated and the boulders more fully weathered toward the bottom. This site is in a zone where rainfall of 50 to 60 inches falls annually, as distinguished from the site of the various excavations for Reservoir No. 4 in Nuuanu, where the rainfall is around 150 inches. It appears, therefore, that the somewhat less weathered rock of the lower part of the thick cap rock cover at the Halawa portal may well be as old as the more weathered rock of the higher rainfall belt in the large borrow pit at No. 4, which, in the writer's observation, has stood as a type for this older alluvium.

In certain places about 5 feet above the floor of the open cut at the tunnel face, the matrix of the gravel consists largely of red, granular, palagonitic tuff resulting from an explosive eruption which was most likely one of the Salt Lake series, probably the same as the earlier one indicated in various cuts east of Halawa Valley. Above

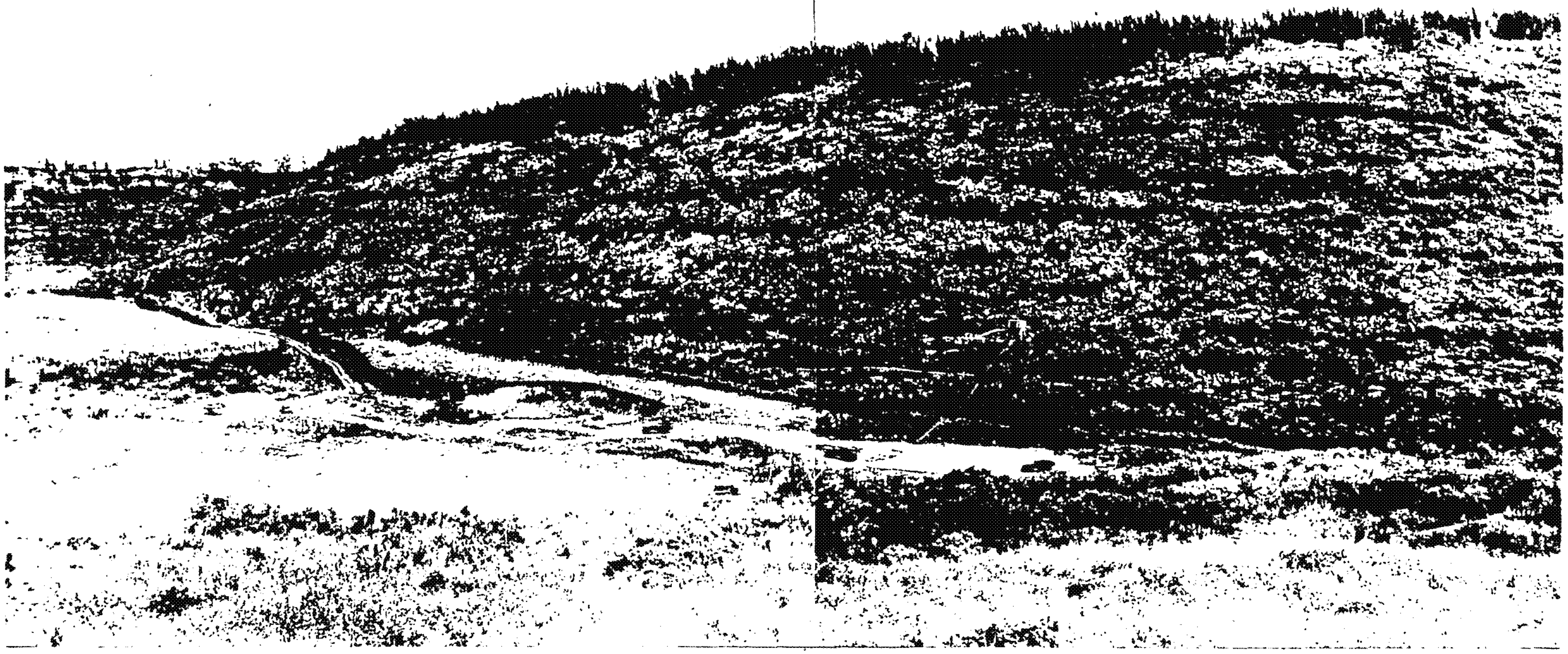

Figure 43 - View of beginnings of portal cut for Halawa Shaft, taken May 26, 1942.
Negatives No. 21399-400.

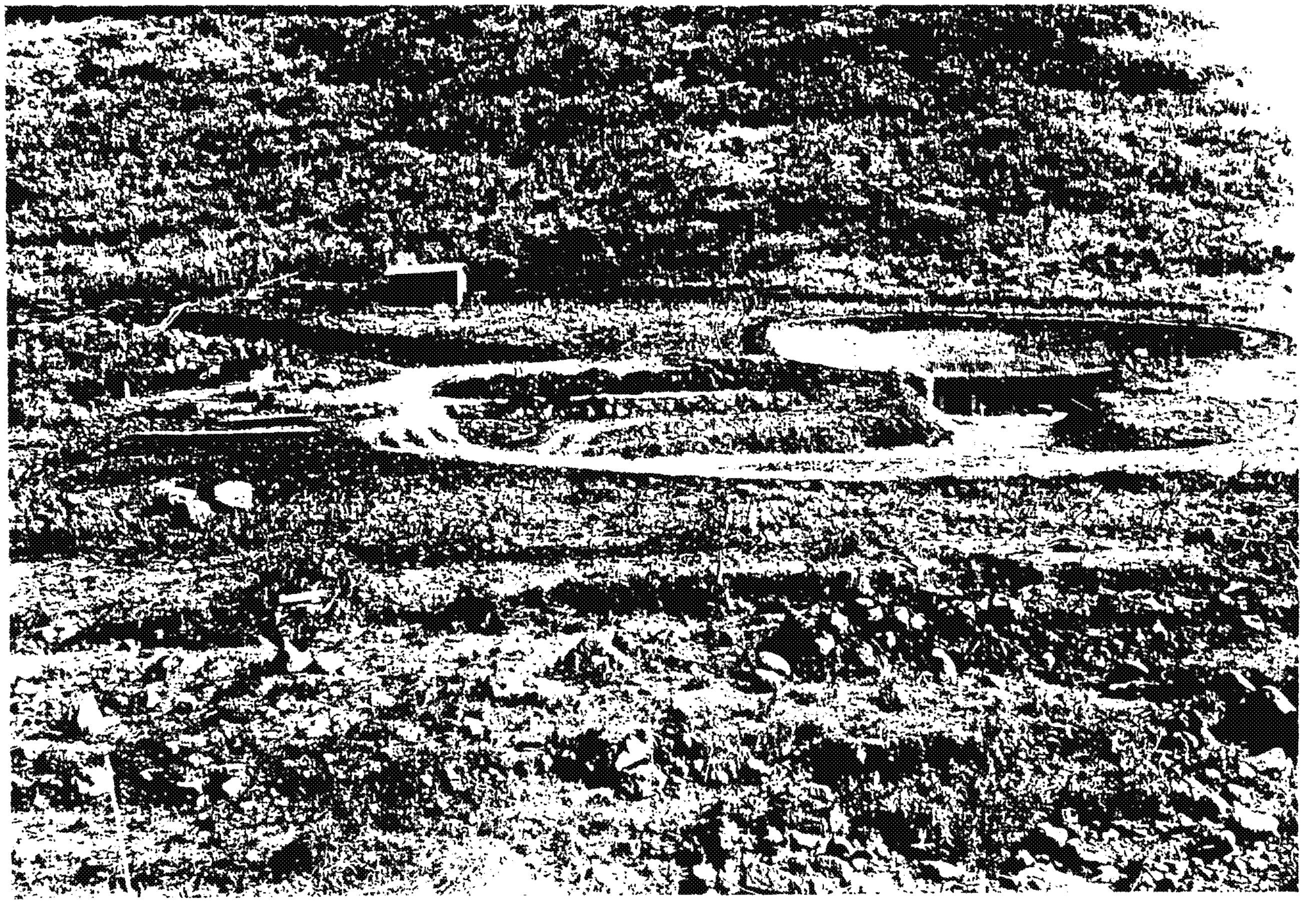

Figure 44 - Completed portal cut, Halawa Shaft.
Photo taken June 26, 1942. Negative No. 21442.

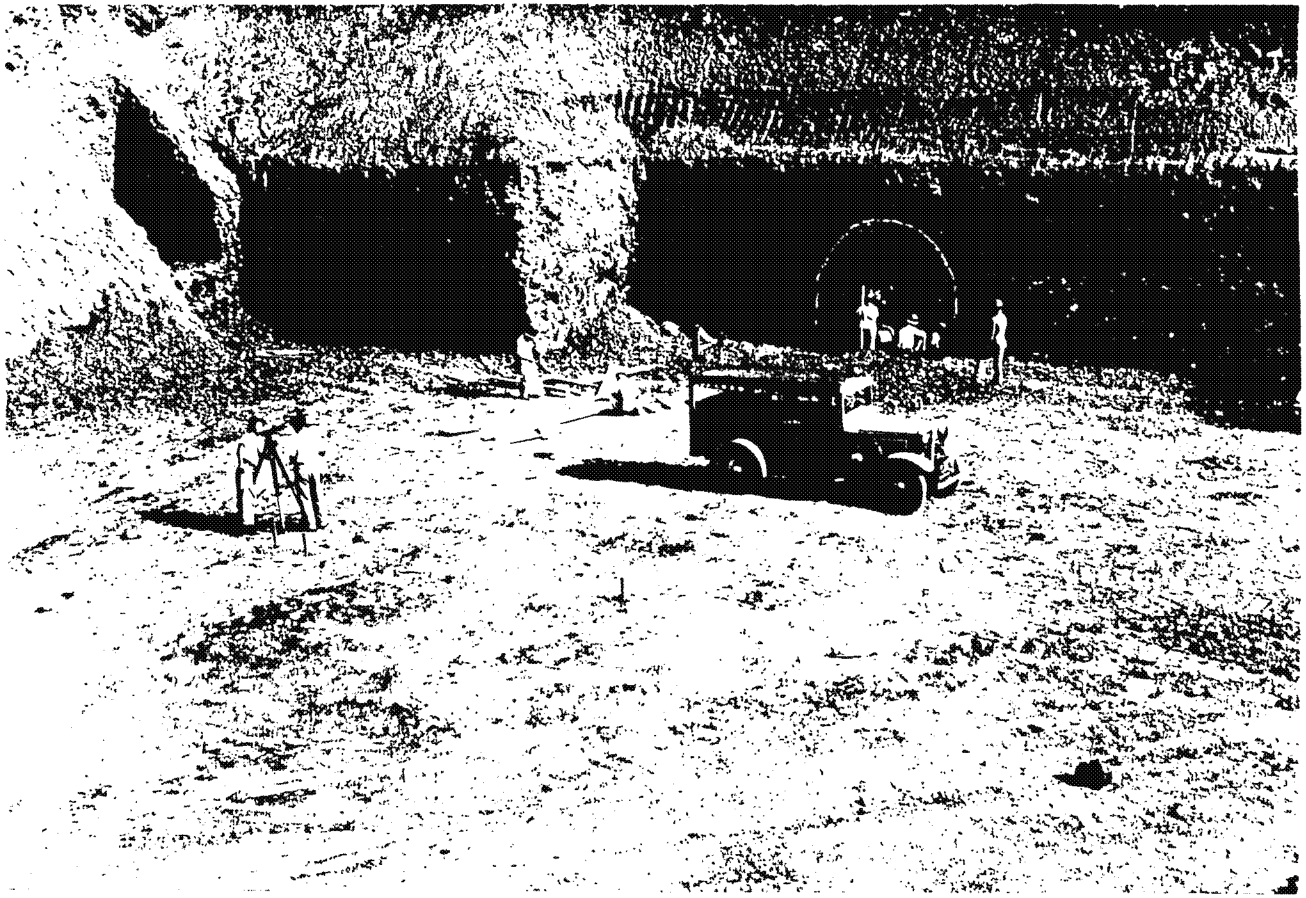

Figure 45 - Rear wall of portal cut, Halawa Shaft, showing outline of shaft portal. Photo taken June 26, 1942. Negative No. 21438.

this tuffaceous layer, the normal gravel overlaps, to be followed 10 or 15 feet higher up by several lenses of nearly pebble-free tuff which probably represents a later eruption of the series. The section, even with these changes in matrix character and indication of explosive ash falls, is so continuous and free from general physical break that it is difficult to interpret in any detail. The upper part is the result of very recent to concurrent accumulation, and the lower part, where it rests on the bedrock of the old valley wall represents the earliest accumulation after the completion of the major, post-Koolau cutting. It appears, therefore, that this cut carries the continuous history of probably all of middle and late Pleistocene time and recent time, a span of probably a half million years or more, but in a condensed and unfortunately not well-punctuated text.

NAVY HALAWA SHAFT (1)

This shaft was driven on a 30-degree incline, at a point a short distance inland from Aiea School. The ground elevation is 95 feet,

(1) This shaft is exactly on the line between the land divisions of Halawa and Aiea. It is called officially the Halawa Shaft by the Navy, but it is closer to other features identified with the village of Aiea, and its position would be better indicated and with less confusion with the North Halawa Shaft of this office, if it were designated Navy Aiea Shaft.

and the shaft penetrates Koolau rock at the inland edge of the cap rock. The sump is supplemented by 42 feet of tunnel with its floor at 16 feet above sea level. A test reported by Stearns (2) showed a drawdown of

(2) Stearns, H. T., Op. Cit., p. 25, 1940.

11.12 feet for a discharge of 21 M.G.D. A comparison of exposed sump and tunnel areas, drawdown and discharge relations for the Waialae and Kalihi basal shafts of the Board of Water Supply, and the Navy Halawa basal shaft made by W. H. Samson showed that the Koolau basalt has very similar values of permeability at each of these stations, the differences being little if any more than the possible errors of estimate of area or other conditions (1). Daily pumping draft from the

(1) Personal communication, July 28, 1942.

Navy Halawa shaft averaged 0.46, 3.12, 6.04, and 8.04 M.G.D. for the years 1938, 1939, 1940, and 1941; and in June 1942, the rate was 9 M.G.D.

HONOLULU PLANTATION COMPANY AIEA SHAFT

This is a vertical shaft driven from elevation of 195 feet in the left side of the floor of a small branch of Aiea Stream about 2700 feet northeast of Aiea Post Office. The cross-section of the shaft is 8 feet by 20 feet. Four short tunnels each 25 feet long, are being driven at basal water level from the bottom of this shaft. At present, October 5, 1942, this station is not in operation for lack of pipe.

ARTESIAN BASAL WATER

There are 73 artesian wells in this area, as shown in the accompanying table.

INVENTORY OF ARTESIAN WELLS

Moanalua District

Number (1)	Status (1940)	Head (2)	Discharge (M.G.D.) (Average 1937-1938)
Moanalua Area (Isopiestic Area No. 4) - (Kalihi-Kahauiki Divide to Red Hill)			
145	Sealed (1928)	-	-
146	Domestic U. S. Army	28.35	0.62
147	Sealed (1929)	-	-
148	Irrigation	28.36	0.50
149	Irrigation	28.49	0.51
151	Unused	28.05	-
152	Sealed (1929)	-	-
153	Domestic	28.48	0.61
154	Irrigation	-	0.26
155	Domestic	28.19	0.03
156	Industrial U. S. Navy	28.23	0.06
157	Irrigation	29.55	0.6
158	Irrigation	28.32	1.13
159	Irrigation	24.77	0.03
160	Domestic U. S. Army		
161	Sealed (1941)	-	-
162	Unused	-	-
163	Unused	-	-
164	Sealed (1937)	-	-
165	Sealed (1937)	-	-
166	Sealed (1937)	-	-
167	Unused	-	-
168	Unused	-	-

(1) New Number series.

(2) Simultaneous head survey, August, 1938.

INVENTORY OF ARTESIAN WELLS

Halawa District

Number (1)	Status (1942)	Head (3)	Discharge (M.G.D.) (Average 1937-38)
Halawa section (Isopiestic Area No. 6) (4) - Red Hill Divide and artesian barrier between No. 4 and No. 6 to Aiea Bay.			
169	Unused (U. S. Navy)		
170	Unused (U. S. Navy)		
171	Sealed (1939)		
172	Sealed (1939)		
173	Sealed (1939)		
174	Sealed (1939)		
175	Sealed (1939)		
177	Irrigation		Est. less than 0.0005
178	Unused		
179	Unused		
180	Sealed (1939)		
181	Unused		
182	Unused		
183	Unused		
184	Unused		
185 A to Q 17 wells	Irrigation, H.P. Co. Pump 1		7.535
186 A to H 8 wells	Irrigation, H.P. Co. Pump 3		8.725

Number (1)	Status (1942)	Head (3)	Discharge (M.G.D.) (Average 1937-38)
187 A to C	Domestic (U. S. Navy)		3.55 (5)
188	Unused		
189 A to E 5 wells	Irrigation, H. P. Co.		5.005

(1) New Number series.

(2) Simultaneous head survey, August, 1938.

(3) Head measurements as near to August, 1938, as available.

(4) Use of the designation Area No. 6 is for descriptive convenience but commits the writer to no particular interpretation as to its isopiestic character or boundaries separating it from Area No. 4.

(5) This station, following completion of the Navy Halawa shaft, declined in discharge to 0.25 M.G.D. in 1940, with a rise to 0.88 M.G.D. in 1941.

INVENTORY OF BASAL SHAFTS

Moanalua District

Name	Owner and Use	Capacity (M.G.D.)	Average Discharge Jan.-June, 1942 (M.G.D.)
Kalihi Underground Shaft (1)	Board of Water Supply Municipal Service	10	6.20
Fort Shafter Refrigeration Deep Well	U. S. Army Emergency Standby and Minor Incidental Refrigeration Plant Use		Not in service August, 1942
Red Hill Underground Shaft	U. S. Navy	20	Excavation of tunnel in progress, August, 1942
North Halawa Underground Shaft	Board of Water Supply Municipal Service	20	Under construction
Navy Halawa Shaft	U. S. Navy Domestic and military Pearl Harbor	17.28	7.86
Aiea Shaft	Honolulu Plantation Co. Domestic and Irrigation		Excavation completed, pump not installed, August, 1942

(1) This station is located in the Kalihi District, but a large part of the rainfall intake area tributary to this station is in the Moanalua District.

SUMMARY OF ARTESIAN WELLS, MOANALUA AND HALAWA DISTRICTS

Status of Wells	Moanalua District Portion of Moanalua Area (No. 4) west of Kalihi-Kahauiki Divide	Halawa District Pearl Harbor Area (No. 6) to east shore and Aiea Bay only	TOTAL
Board of Water Supply	0	0	0
U. S. Navy	1	5	6
Used		3	
Unused		2	
U. S. Army	2	0	2
Other public ownership	0	0	0
Private ownership	13	38	51
Domestic	2	0	
Industrial	0	0	
Irrigation	6	31	
Unused	5	7	
Sealed	7	6	13
Total	23	49	72

A total of 72 artesian wells have been drilled in the area under consideration in this report, 23 in the Moanalua portion and 49 in the Halawa portion. Of the total in the Moanalua sections, 7 have been sealed and 5 are unused; of the 11 in use, 6 are used for irrigation, 2 are private domestic, 2 are domestic U. S. Army, and 1 is industrial U. S. Navy.

Of the 49 in the Halawa section, 6 are sealed and 9 are unused; of the remaining 34 in use, 31 are used for irrigation and 3 for Pearl Harbor general supply, U. S. Navy. The following table shows the approximate controlled discharge of both artesian and free basal water for the Moanalua and Halawa districts, for comparison with the rainfall figures deduced for the same sector of the Koolau Range.

DISCHARGE OF BASAL WATER IN THE MOANALUA-HALAWA AREA

Annual Average, 1941

	Domestic	Domestic-Military	Industrial	Irrigation	Municipal	Total Artesian	Total Free Basal	TOTAL
Moanalua District Moanalua Area (No. 4) Kalihi-Kahauiki Divide to Red Hill Divide.								
Artesian Wells	0.34	1.04	0.15	2.25		3.78		
Basal Shafts					3.98		3.98	
								7.76
Halawa District Pearl Harbor Area (No. 6) Red Hill to East shore and Aiea Bay.								
Artesian Wells		0.88		17.94		18.82		
Basal Shafts		8.04					8.04	
								26.86
	0.34	9.96	0.15	20.19	3.98	22.60	12.02	
GRAND TOTAL								34.62

The boundaries of this district are such that none of the sites of the Pearl Harbor Springs are included in it. The Kalauao Spring is about a half mile to the northwest of the limit of this district, and though it is possible that some of the water discharged from it may come from the Halawa rainfall area, it is most likely that no significant part of it does. Since the problem of the springs will be dealt with in the next report, it will be assumed that the discharge of none of the large, named springs is supplied from the Moanalua-Halawa area. On this basis, the total basal discharge, in sight, from the Moanalua-Halawa District in 1941, was 34.62 M.G.D., derived from a total mountain rainfall of 79.49 M.G.D. These quantities will be discussed more in detail in the next section.

The writer's general views on the artesian and basal water system have been set forth elsewhere (1), and do not need to be

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(1) Wentworth, C. K., Manoa-Makiki Report, pp. 126-135, 1940, Kalihi Report, p. 87, 1941.

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repeated here.

CAP ROCK WATER

Very few data are available on cap rock water in this area, though some casual use of such water is made at a few points. Use of cap rock water is considered desirable wherever basal water can be conserved thereby and where it can be done without damage to the basal and artesian system. The writer's general views on the use of cap rock water for irrigation, cooling and other purposes have been stated in an earlier report.

SUMMARY AND RECOMMENDATIONS

ESTIMATES OF WATER QUANTITIES

In making an inventory of water supplies and water use for the Moanalua-Halawa district, no better basis is known than to assume that the usage along the coastal plain and coastal margin of the two districts is chargeable against the rainfall intake in the inland topographic watershed of the two areas. It is not likely that the ground-water divide between windward and leeward Oahu lies everywhere precisely under the topographic crest of the range, and it seems possible that a small area of some parts of the windward slope may receive rainfall which ultimately reaches the leeward basal ground-water body. However, this possibility becomes progressively less to northward of the Honolulu area because of the converging of the dike complex toward the crest of the range, and we have no basis for postulating any particular line as the ground-water divide.

It is also true that the lines down the steepest slopes of the basal water table may not precisely coincide with the crests of the secondary ridges that form the topographic boundaries between Kalihi and Kahauiki-Moanalua, and between Kalauao and Halawa, but we do not know whether they overlap so as to bring more or less water into this district. The estimates of rainfall are based on the best available rainfall data, which are rather scattered. A short record of three months on the two newly established rainfall stations (p. 95) by comparison with the North Halawa stations suggests the possibility that maximum rainfall in the inland zone of the Halawa area may be greater than that indicated by existing records as shown on Figure 42, but is wholly inadequate to justify any attempt to estimate what the effect might be on total water quantities.

TOTAL BASAL DRAFT
MOANALUA (No. 4) AND EASTERN PEARL
HARBOR (No. 6) AREAS

Unit	Domestic	Industrial	Draft Irrigation	Domestic-Military
Well 141			0.08	
Well 142			0.44	
Well 143		0.14		
Kalihi Basal Shaft	6.2			
Well 146				1.04
Well 148			0.39	
Well 149			0.34	
Well 153	0.31			
Well 154			0.05	
Well 155	0.03			
Well 156		0.15		
Well 157			0.50	
Well 158			0.97	
Well 159			0.003	
Well 160 ?				
	6.54	0.29	2.773	1.04
Well 177			0.001 (1)	
Wells 185A to Q			4.86	
Wells 186A to H			8.41	
Wells 187A to C				0.88
Wells 189A to E			4.67	
Navy Halawa Shaft				8.04
			17.941	8.92
	6.54	0.29	20.714	9.96

The total rainfall estimate for the 5.58 square miles of mountain area of basal water intake for Moanalua District is 37.13 M.G.D., for the similar portion of 6.17 square miles of Halawa district is 42.36 M.G.D. and for the two is 79.49 M.G.D. If we add to the Moanalua district, for the mountain area, 1.29 square miles of West Kalihi, and 0.87 square miles of the south side of South Halawa, we then have the mountain area presumably tributary to the Moanalua (No. 4) artesian area, and by similar additions have a total mountain rainfall of 49.92 M.G.D. By subtraction of the same portion of South Halawa, we get for the eastern part of Area No. 6, a mountain rainfall of 36.58 M.G.D. These are the figures deemed most comparable with the draft figures for the two basal areas, and by a similar computation to that used and described in earlier reports, it is concluded that the amounts of infiltration in the Moanalua basal area and the eastern part of No. 6 are most probably 22.66 and 13.38 M.G.D., respectively.

In the Moanalua Area, at the end of 1941, the total recorded public and private draft averaged 10.64 M.G.D., slightly less than half the estimated increment from infiltration. On the other hand, the eastern part of the Pearl Harbor area has a discharge of 26.861 M.G.D., which is double the total estimated increment. For the two areas, the recorded draft is 37.50 M.G.D., or slightly over the estimated infiltration of 36.04 M.G.D.

It became evident in preparing the Kalihi Report that the Moanalua district was one in which there was a relatively large mountain rainfall and less artificial draft than in the three central Honolulu areas, as shown in the following table.

Isopiestic Areas

	East Pearl Harbor "Halawa"	Moanalua No. 4	Kalihi No. 3	Beretania No. 2	Moiliili No. 1	Waialae No. 5
Estimated basal infiltration	13.38	22.66	4.32	7.62	2.84	2.59
Recorded basal draft	26.86	10.64	8.51	9.40	6.03	1.5 (1)

(1) Estimated from incomplete data.

Each of the three central areas appears to sustain more draft than the estimated annual increment from rainfall, a condition which strongly suggested some such mechanism as the bottom storage behavior, as set forth elsewhere (1). It will also be noted that the greatest

(1) Kalihi Report, Appendix 2, pp. 109-137, 1941.

disparity occurs in the Moiliili area, which has long been recognized by operating pump engineers and others as the "weakest" area of those in Honolulu, i.e., as having the least head stability against increased draft.

Now in returning to the Moanalua Area, where draft is less than half the estimated infiltration, we might be greatly encouraged but for the recognition made possible by this joint report on the

Moanalua-Halawa areas, that the Halawa area is apparently one of large draft and relatively less adequate rainfall and infiltration. The conclusion seems inescapable that much of the deficiency of the Halawa area is supplied by lateral leakage from the Moanalua area along their common boundary.

It should be recognized that the Halawa area is only a part of the Pearl Harbor area and that it is not cut off sharply by any known valley-bottom barrier. Until an analysis of the Pearl Harbor area is completed, it is impossible to draw any final conclusion as to supplies available in the Halawa area. The question of the Pearl Harbor Springs is involved, and additional data will shortly be available from operation of two or three of the new shafts in the Red Hill-Halawa area. Another approach has been made to the hydraulic behavior of the Honolulu and Pearl Harbor areas in Appendix 1, of this report.

SUMMARY OF RELATION BETWEEN MOANALUA AND PEARL HARBOR AREAS

Several geologic contrasts between the Pearl Harbor and Honolulu areas have been mentioned elsewhere. They are listed below.

(1) Honolulu has a narrower coastal plain, but it is intact and broken by few inlets of salt, brackish, or fresh water.

Pearl Harbor has a wide coastal plain, cut by the widespreading arms of the harbor.

(2) The Honolulu sector is cut by several deep valleys, having broad valley flats at the mouth, and known from drilling to have cap rock tongues filling them to depths from 300 to 1000 feet below sea level.

The Pearl Harbor sector is cut by numerous valleys, longer in their mountainous section than those of the Honolulu area but with narrow flats at the mouth and mostly cut less deeply below sea level and having cap rock tongues, if any, that are but a few feet below sea level and that extend only a moderate distance inland.

(3) In the Honolulu sector, Koolau rock is overlapped nearly everywhere to elevations of 100 or more feet above sea level.

In the Pearl Harbor area, Koolau rock is exposed very near to sea level and to the shore of Pearl Harbor in many places.

(4) The Honolulu area shows a sharp separation into several isopiestic areas, within each of which the static level of wells is commonly uniform within 0.2 feet, and each of which, according to conditions may have its level changed materially in relation to adjacent areas.

The Pearl Harbor area, while exhibiting some systematic and some ephemeral changes of level, is not apparently divided into distinct isopiestic areas.

(5) The static heads in the Honolulu area are materially higher than those in the Pearl Harbor area. (Cf. 1 and 3)

(6) The static head of the central area of the Honolulu system and probably of the other areas was prior to 1880 at least 12 feet higher than prevailing levels of the past 20 years.

There is no record or evidence that the original static head in the Pearl Harbor area was materially higher than now.

(7) The response of the static level in the Pearl Harbor area to excess of draft, and its subsequent recovery from the same seem more rapid than similar responses in the Honolulu areas.

(8) The length of shore line in the Honolulu area is about the same as the width of the corresponding inland watershed. The area of basal infiltration per mile of shore line is about 2.0 square miles.

In the Pearl Harbor area the drainage of a very large area, much wider than the coast line length, and from longer streams than those of the Honolulu watershed converges on the Pearl Harbor outlet. The area of basal infiltration per mile of shore line is of the order of at least 5 or 6 square miles.

(9) The average chloride content for the Honolulu area is about 60 parts per million. The average for all water discharged in the Pearl Harbor area is of the order of 400 parts per million, with only a minor fraction of the total with chloride content as low as 100 p.p.m.

(10) The average annual rainfall of the mountain watershed in the Pearl Harbor sector is undoubtedly higher than in the Honolulu sector. Detailed analysis is not completed, but the average may be 10 to 15% higher.

(11) The multiple correlation in Appendix 1 shows clearly that under comparable rainfall conditions, the currently available water supply of the Pearl Harbor area is approximately 5 times that of the Honolulu area.

(12) The above fact indicates that a much larger percentage of total rainfall is available in the Pearl Harbor area than in the Honolulu area, since there is nothing to indicate that total rainfall of the Pearl Harbor area is more than possibly about 3.5 times that of the Honolulu area.

The various contrasts listed are not all independent, some of them are causes of the others. The composite result appears to be that the amount of water daily moving through the Pearl Harbor system may be from 3.5 to 4 times as much as that moving through the Honolulu system, and since the depth of water-saturated rock is less in the Pearl Harbor system, it is valid to suppose that general velocities of seaward movement may be at least 4 times as great. The movement in the Pearl Harbor area is probably more concentrated in the sea level zone because of larger known leaks as in the Pearl Harbor Springs. The functioning of bottom storage is relatively less important in the Pearl Harbor area. Draft from the Pearl Harbor system is more like draft from a large river; that from the Honolulu system is more like draft from a large lake. The equilibrium of the former is more dynamic; that of the latter more static. These differences suggest differences in management in order to get the maximum benefit from the available increment and storage water.

OPERATIONAL PROCEDURE

The paramount question is how to get the most water of acceptable quality on the average, without depleting the storage margin that is considered essential for safety against extreme rainfall deficiencies and against emergency increases of draft. Opinions differ as to what is acceptable quality and what is a safe margin against rainfall deficiencies. Conditions in the Honolulu system differ somewhat from those in the Pearl Harbor system. The graphs of Figures 1 and 2 in Appendix I show that the head in the Pearl Harbor system is less responsive in amount to comparable changes in rainfall and draft than head in the Honolulu system. On the other hand, the records show that much more severe head changes are experienced in the Pearl Harbor system than in Honolulu. (See Table below)

	Honolulu System	Pearl Harbor System
Mean Annual Head Range (Feet)	2.47	4.53
Maximum Annual Head Range (Feet)	3.68	8.00
Mean Annual Range of Monthly Average Draft (Ratio high to low)	1.37	4.42
Maximum Annual Range of Monthly Draft (Ratio high to low)	1.52	9.54

These marked head changes in the Pearl Harbor system are readily explained by the very much larger ratios between high and low draft, the greater part of the draft being for agricultural purposes and far more responsive in opposite sign to rainfall fluc fluctuations.

The compiled data and the graphs show that the Pearl Harbor system yields for useful application on the average about 5 times as much water as the Honolulu system. From the standpoint of securing a specific amount of additional water, this larger system is more attractive, but in terms of a relative increase, such as 20% in the two areas, the graphs suggest that this would require (under present conditions; effect of a new station is not fully known) a continuous head depression of 1.15 feet in the Honolulu, and 0.93 foot in the Pearl Harbor areas, amounts which are nearly proportional to the two mean absolute heads of 27.56 and 21.08 feet for the period 1925 to 1940.

Examination of the watershed of the Pearl Harbor system is not complete, and full analysis of probable rainfall intake is not completed but the writer has estimated that the total rainfall of the mountain portion of the Pearl Harbor system is at least 3 times that of the Honolulu system. Since there is no basis for believing that the total Pearl Harbor mountain rainfall can be as great as 5 times that of the Honolulu area, it appears that the artificial yield from the Pearl Harbor area is a much greater percentage of rainfall than in the Honolulu area, despite the apparent greater perfection of the cap rock and higher heads of the latter area. The larger amount of water of the Pearl Harbor area is concentrated in its seaward margin so that it apparently passes through a coastal section of almost equal length to that of Honolulu. This greater concentration of flow would undoubtedly lead to higher heads if the higher parts of the cap rock were equally effective as barriers. This, however, is not the case, and the various overflow springs, somewhat larger probably in early days, apparently set a limit to the Pearl Harbor basal head. With such a condition, a slight general head reduction would probably make available a large amount of water, and that is probably at least in part the explanation for the larger amount of draft, relative to rainfall, which the Pearl Harbor system seems able to furnish.

However, with the system as at present constituted, with the bulk of the water still coming from artesian wells, the draft is gained only at the expense of an average chloride content of about 400 parts per million, as compared to not over 60 for the Honolulu area, a ratio of over 6 to 1.

Data on chloride content from the Navy Halawa Shaft (93), Waiau Hawaiian Electric Shaft (134), and Ewa Shaft (184), as the three chief producing basal shafts in the area, do not give confidence that the discharge from the Pearl Harbor system would, even with sealing of all wells be so low in chloride as that of the Honolulu area. The Ewa Shaft is driven only 2.9 feet above sea level, and the Waiau Shaft is expanded by wells drilled below sea level, so that a higher chloride content might be expected in either of these rather than in the Navy Halawa Shaft. In shafts driven to basal water some distance inland from the Koolau margin and with spread excavation arranged for skimming, the chloride content of Pearl Harbor basal water may run prevailingly somewhat under 100, or less than twice that of the Honolulu area (1).

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(1) First valid test on uncontaminated flowing basal water at the new North Halawa Shaft on September 23, gave a chloride content of 103 P.P.M.

The recurrent problem, which comes successively to different independent agencies, as to where additional needed water supply can be obtained without damage to existing supplies is one for which there is no real solution, only an apparent solution. Development of additional basal water, meaning water not now in use or subject to use, in the Pearl Harbor or Honolulu area is probably no longer possible. Construction of additional stations for the draft of either the same or additional amounts of water with the least interference with other stations and with the most efficient control of water quantities and qualities is practical and will be extensively done in the future. The notion that water could be developed in hydraulically adjacent areas, in each without effect on the other, has taken long to be recognized as fiction.

Because of the constant fluctuations of rainfall and draft, the actual effect of a new draft is obscured and perhaps is regarded as unimportant if water is abundant. When water becomes scarce, or appears to be so because of operating conflicts, the situation may be relieved by the development of water from hydraulically isolated sources. When this is impractical, an improved and coordinated operation of the fundamental supply is the only permanent recourse. Honolulu and the Pearl Harbor area are in the process of proving this latter proposition by the construction of three new basal stations, Red Hill, North Halawa, and Aiea. These three stations will be in a position to draw more water more advantageously from the basal water table between Kalihi Valley and Pearl City, but there is no reason to believe that it will be water not already accessible to pumps at Kalihi Underground Station, Well 146, Wells 187 A., B., C., and Navy Halawa Shaft.

The cost of the additional stations, without regard to ownership or use of the water, will probably be amply repaid by the generally more flexible pumping conditions and larger reserve capacity for emergency use, by the greater capacity of the stations for deforming the basal water table in favor of a particular area as needed, and by the very valuable understanding of basal water behavior which will result from analysis of records made during normal and special operation. Only by such practical tests can a valid determination be made as to the most economical and socially expedient operating schedule. In the writer's mind at present are four chief questions, as follows:

I. What improvement of the Pearl Harbor system can ultimately be accomplished by actual repair of leaks at the Pearl Harbor Springs? This question can best be discussed after the western Pearl Harbor area has been more fully studied. The writer has in mind, not merely reduction of leakage through reduction of head, by drawing water from the springs or from the depression figure near them, but actual isolation of the springs to allow water sealing up to the basal head, or repair in some other manner.

II. What division of draft between North Halawa and Red Hill, or between Area No. 6 and Area No. 4 is most advantageous? It has been stated elsewhere that a considerable amount of water, possibly 10 to 20 M.G.D., may move laterally from the Moanalua district to the Halawa district. If this is the case, and from this standpoint alone, it should be advantageous to lower the Moanalua head by use of the Red Hill station. On the other hand, if heavy draft is taken from the North Halawa station and the basal water table is lowered here in relation to the area west of Aiea, flow may be sufficiently modified so that additional water will be pulled toward this station from the central Pearl Harbor area. This consideration might make extra draft from the North Halawa station desirable, even if both the Red Hill and North Halawa stations were under the control of one agency.

III. What improvement will be wrought and to what extent will additional lowering of basal heads in the four areas of the Honolulu system be justified, when (A) all municipal draft is from basal shafts, (B) private draft from wells is negligible, (C) interconnection with Red Hill and operation of the North Halawa Shaft offers additional safety against periods of rainfall deficiency?

IV. What are the facts of bottom storage and of the movement of the diffusion zone and what bearing do these data have on the long-term aspects of the three questions formulated above?

RECOMMENDED PROCEDURE

In the light of findings in the Moanalua-Halawa area and the problems posed in the Pearl Harbor area, the following operational and investigational procedures are recommended:

Moanalua-Halawa District

1. No conditions were found which indicate that a profitable development of high-level water can be accomplished in either the Moanalua or Halawa districts.

2. Until more data are available from practical operation and observations of basal head, no further basal stations or additional basal or artesian water development can be recommended beyond the three stations now under construction, Red Hill, North Halawa and

Aiea. These stations, with Kalihi and Navy Halawa, make five basal shafts in a distance of 5.5 miles, at intervals respectively as follows Kalihi-Red Hill, 2.7 miles; Red Hill-North Halawa, 0.9 mile; North Halawa-Navy Halawa, 1.3 miles; Navy Halawa-Aiea, 0.6 mile. These stations all told have capacity installed or planned of 100 M.G.D., which is of the order of 3 times the present yield of this area. No other area on Oahu is so favorably situated to determine by full-scale hydraulic testing what increased yield can be gained by lowered heads and what the quantitative relationships between two major isopiestic areas are.

3. The largest gap in the line of basal stations is that between Kalihi and Red Hill; experience in operating the several stations now constructing will furnish the only valid answer to the question of whether the economics of supply and distribution will justify a major basal station in Manaiki Valley, perhaps in the north-west wall, about 0.7 mile inland from the inland margin of Moanalua Gardens.

4. Under the operating conditions suggested by the several large-capacity stations under construction, it is highly important that continuous observations be made on the rainfall of the intake area, on the basal head at definitive points across the district and that continuous compilations be made of the draft, drawdown, and salt data for all the important producing units. The number of rainfall records previously collected northwest of Kalihi is insufficient for detailed studies; the addition recently of two stations in the mountain section of North Halawa and the commencement of rainfall measurements at the Haiku Tunnel intake will greatly improve this condition.

Consideration is being given by this division to the establishment of an inland station in the head of Moanalua Valley at about 1 mile from the Koolau Range crest.

Measurements of basal head have been made twice weekly at five test holes for the past few weeks and at some of these for a longer period. These measurements define rather accurately the form of the basal water table during a somewhat dry year, with known pumping schedules at Kalihi Underground Station and at Navy Halawa Shaft and various wells. To determine the changes in form wrought by draft from any or all the additional stations, these measurements should be continued, and the possibility that additional test holes will be needed should be kept in mind. In particular, as much data as possible should be collected on the static water level in the North Halawa Shaft in advance of draft, so that its quiescent relation to the Navy Halawa Shaft, the Aiea "Austin" Hole, and to the Aiea Shaft shall be known.

Honolulu System in General

5. With the emergency modification of program which will result in construction of the North Halawa Shaft and interconnection with the Red Hill, Fort Shafter, and Pearl Harbor systems, emphasis on Honolulu projects may be somewhat changed. In this writer's opinion, the most urgent project is the extension of the Waialae Tunnel as previously planned. This project, with No. 6 and No. 7, will greatly strengthen the supply for the eastern part of the Honolulu district.

6. Construction of the Palolo (Waiomao) Recharge Tunnel, concurrently with the lengthening of the Waialae Development Tunnel, to increase the supply available at Waialae Basal Station.

7. It is increasingly evident that the entire Honolulu low-level supply will eventually come from basal underground stations rather than artesian wells. It is believed that the station strategically next most desirable for construction is that in the east wall of Manoa Valley, corresponding to the Moiliili Artesian Area (No. 1). This station would facilitate safe draft of the Moiliili head to lower levels, and would decrease the head difference between areas No. 1 and No. 5. Combined with the transmission tunnel under Mauumae, and with projects 5 and 6, this project would greatly improve the water supply situation east of Diamond Head.

8. Install in one or more existing, non-used deep artesian wells, probably in the Beretania area, a small pipe attachment for frequent or continous, systematic sampling of the artesian water for chloride content, at least at one depth, but preferably at several depths. The commencement on a continuing basis of such a project of recording the surmized movements of the diffusion zone is believed to be the only direct approach to the problem of quantities of stored fresh water in the Ghyben-Herzberg lens. Measurements of this kind, made by methods that avoid drastic disturbance of the conditions it is desired to measure, would be of great value in guiding the control of the artesian system, equally whether the theory of bottom storage is, or is not, correct. [Suggested procedures were set forth in the Kalihi (pp.103-104) and Nuuanu (pp. 216-223) reports.]

Pearl Harbor System in General

9. General geologic and hydrologic studies of the remainder of the Pearl Harbor area, comparable to the studies of the Honolulu area and Halawa, reported in this and earlier manuscripts, should be

carried through to completion. The past three of these reports have been completed at intervals of less than one year each. Despite the fact that the area of the remaining Pearl Harbor district is large, lack of special conditions in the Halawa district and increasing general knowledge of the character of the Koolau Range will justify a less exhaustive geologic examination, and it is believed that the remaining Pearl Harbor report can be completed late in 1943 or early in 1944. Its completion will depend somewhat on the program adopted in regard to preparing a report for publication on the Geology and Ground-Water Resources of the Honolulu Watershed.

10. Emphasis should be given to the systematic collection of data on draft, chloride content, and heads, in the Pearl Harbor area as now commenced by Mr. Samson. The head records for Wells 187B, 190, 193, 201, 244, 266, published for each year by the U. S. Geological Survey through the Washington office, and records of discharge published occasionally for periods of years by the local office (1),

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(1) Stearns, H. T., Bulletins 1 and 5, 1935, 1940.

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are valuable as permanent records and for comparison with other national trends but are neither prompt enough nor complete enough to serve the practical need for complete and immediate study of large-scale trends.

11. Rainfall data are deficient for the inland area of infiltration between Kalihi and Kipapa. Two new gages have been installed in the Halawa basin and are being read by this division on approximately a monthly basis. If practicable, one or two more gages will be placed in the Waimano-Waiawa basin to furnish a better transition to the area of more complete gaging back of Wahiawa.

12. (1)With the approach to completion of the three new basal

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(1) Based on discussion with Walter Samson.

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stations, one municipal, one military, and one agricultural, in the eastern part of the Ewa district, and the prospect that considerable amounts of water will be pumped from these, with high rates of pumping in some cases, no one acquainted with the problems of water supply can avoid concern as to what the effects of this pumping will be and what limitations will be required to safeguard a common supply. It has long been recognized that water supply in this area is in no sense confined within property lines, and it has been increasingly evident that competitive development of water supply on the basis of land ownership must yield to a region-wide consideration of water supply and water needs. Long strides in this direction have been made by the provisions for interconnection between the Fort Shafter, Red Hill, and Pearl Harbor military systems and the supply and distribution systems of the Board of Water Supply.

Regardless of whether we have war or peace, there will be increasing need for systematic, long-term studies and plans with reference to the use of the only major water supply the Honolulu and Pearl Harbor areas will ever have. The more promptly these studies are established on an adequate and continuing basis and the more regularly they are made available to the three chief agencies involved, the more effective can plans for future equitable operation of the system be made. It is believed that neither the municipal authorities, the plantation officers, nor the Army or Navy, will sanction further large-scale development of water without the most comprehensive studies of existing and prospective conditions. It is believed that the time is ripe for the establishment of machinery for making such studies and the development of long-term plans for water use and distribution. It is urged that the following steps be taken: (A) Seek legislative sanction, as far as it may be needed, for expanding and continuing hydraulic and hydrologic studies by the Board of Water Supply in the all-around interest of water supply in the Pearl Harbor area. (B) Arrange for the establishment, presumably by legislative action, of a permanent council or committee to represent the chief agencies, municipal, territorial, agricultural, and military for the purpose of from time to time determining an equitable program of procedure in the development and operation of water supply units in the Pearl Harbor area.

13. In order that water supply possibilities in the Halawa area may be determined as promptly as possible and that relief of Honolulu stations be provided in connection with construction under 5, 6, and 7 (above), it is recommended that North Halawa station be operated at a rate of 5 to 8 M.G.D., commencing on its completion.

APPENDIX I

Comparative Multiple Correlations of Head, Draft, and Cumulative Rainfall in the Honolulu and Pearl Harbor Artesian Systems

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Various mathematical approaches to the problems of the Honolulu and Pearl Harbor artesian systems are possible, and some have been tried. It is apparent from the results of some attempts that our data, especially on the position of the lower limit of the fresh water lens, and on areas and porosities of the aquifers, are insufficient to permit significant solutions of more detailed equations. The present correlation is an attempt to sufficiently simplify the assumptions and the questions asked so that a few definite answers can be had.

Assumptions are as follows: (1) That each of the two systems can be treated as a system whose head is an indicator of the current relationship between gain by infiltration and loss by draft. (2) If there be gain or loss by transfer from or to bottom storage, or if there be natural leakage, or unknown, unrecorded losses through faulty wells, it is assumed that these are constants which will be included in the constant of the equation. Insofar as they are not constants, the deviations will be included in the errors, along with those of measurement. (3) That relationships between infiltration and rainfall are linear and that rainfall can be used as a measure of infiltration. (4) That the rainfall effect is a cumulative one, with the effect declining into the past as a logarithmic decrement, therefore; the cumulated rainfall from the average normal rainfall expectancy, each reduced by 4% compounded for each month since it occurred. The yearly value of $R_{c.m.}$ used in the calculations is the average of the twelve monthly values for that year. (5) That Head can be represented by the average for certain wells. The equation follows.

$$\text{Head} = x + y\ (R_c) + z(\text{Draft})$$

The period taken was from 1925 to 1940, since data are very scanty before 1925; and even from 1925 to 1928, a considerable number of interpolations and substitutions of index wells were required. In the Honolulu system, the solution was based on the years 1926-1940, each inclusive.

After compiling the data, computing the averages of rainfall stations for each area (1), the percentage relationships of the

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(1) Stations used for the Honolulu system were Kalihi Valley (430'), Kapalama (520'), Lower Luakaha (894'), Nuuanu Reservoir No. 5 (413'), Tantalus (1360'), Manoa (300'), with an actual average for the period 1925-1940 of 92.12 inches.

Stations used for the Pearl Harbor system were Aiea (500'), Waimalu (500'), Waipahu (60'), Waikane (800'), Waiawa (725'), Waianae-Uka (2310'), Koolau Dam (1150'), Wahiawa Water Company Intake (1200'), Schofield Barracks (892'), Upper Hoaeae (705'), with an average for the period 1925-1940 of 104.07 inches.

These stations are not ideally located for the purpose but are the best available for the whole period. Since the whole calculation is carried out in terms of deviation from the average, these stations should not be regarded as giving an average rainfall for the area, or as giving a total quantity having absolute validity. This method seemed likely to give more useful comparability between the two areas and to be better adapted to transfer to other series of index stations should these become available.

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average for each month to the normal, and computing the cumulative rainfall for each month, the following tables.

HONOLULU SYSTEM

Areas 1, 2, 3, 4

Year	Mean Head (Feet) H	Cumulated Rainfall Mean for Year (1) R_c	Mean Total Draft (M.G.D.) D
1925	23.9	− 0.79	
1926	23.0	− 3.90	38.4
1927	24.3	− 1.27	36.8
1928	27.7	+ 0.89	34.4
1929	26.2	− 1.33	33.4
1930	27.8	− 0.52	31.2
1931	27.4	− 0.79	32.1
1932	29.4	+ 2.04	29.6
1933	28.8	+ 0.55	28.7
1934	26.6	− 1.92	28.6
1935	27.4	− 0.88	29.5
1936	26.5	− 1.78	30.8
1937	29.6	+ 1.38	29.7
1938	30.3	+ 1.62	31.1
1939	29.6	+ 2.01	30.3
1940	28.8	− 0.06	32.8
Average 1926-1940	27.56		31.83

PEARL HARBOR SYSTEM

Area "6"

Year	Mean Head (Feet) H	Cumulated Rainfall Mean for Year (1) R_c	Mean Total Draft (M.G.D.) D
1925	20.2	− 0.82	178.2
1926	18.8	− 3.92	183.7
1927	20.2	− 1.34	144.9
1928	22.3	+ 1.02	174.7
1929	20.5	− 1.06	177.5
1930	22.0	− 0.39	147.4
1931	20.4	− 2.08	183.4
1932	22.4	− 0.68	158.8
1933	21.4	− 0.70	176.9
1934	20.1	− 2.34	174.7
1935	20.5	− 1.61	168.4
1936	20.0	− 1.84	166.3
1937	23.4	+ 1.31	165.6
1938	23.1	+ 2.61	182.8
1939	21.7	+ 1.93	190.2
1940	20.3	− 0.29	210.9
Average 1925-1940	21.08		174.0

Normal equations were set up in the usual form of

$$\text{I.} \quad \sum H = xN + y\sum R_c + z\sum D$$

$$\text{II.} \quad \sum HR_c = x\sum R_c + y\sum (R_c)^2 + z\sum R_cD$$

$$\text{III.} \quad \sum HD = x\sum D + y\sum R_cD + z\sum D^2$$

The values derived from expanding the foregoing tables were then substituted in the normal equations, and the following solutions were derived:

For the Honolulu System:

$$\text{Head} = 33.30 + 0.897R_c - 0.173 \text{ Draft}$$

(P.E. = 0.41)

For the Pearl Harbor System:

$$\text{Head} = 25.75 + 0.673R_c - 0.0244 \text{ Draft}$$

(P.E. = 0.36)

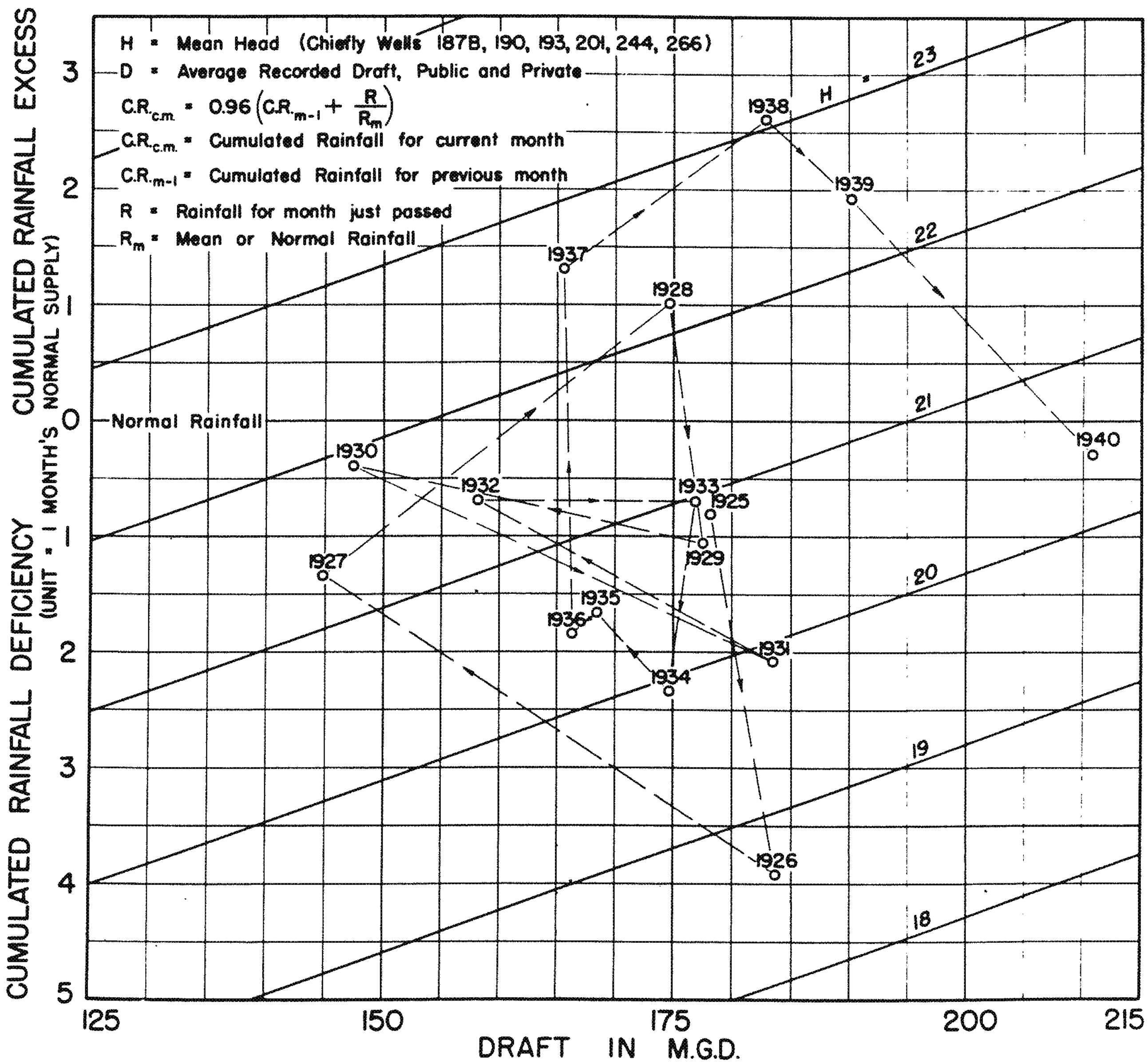
In order better to visualize the significance of these equations, each has been shown in graphic form. (Figures 1 and 2)

In the graphs of Figures 1 and 2, the scales have been so arranged that they and resulting slopes of head lines are comparable, despite the difference in size of the systems and the disparity in absolute values of draft. By making the scale ratio 5 to 1, the range of draft variations in the past 15 years comes within almost identical graphic limits for the two systems, greatly facilitating visual comparison. Thus the draft scale for each of the two systems is essentially one of variation about its own mean. This is exactly what appears in the scale of cumulated rainfall, so that the two graphs are comparable in this respect also.

Interpretation of the meaning of the two equations requires some caution, that they are not taken to mean too much; but equally that they are not dismissed as meaning too little, because of the numerous qualifying assumptions. The first elementary deduction from the graphs is shown in the following table:

	Honolulu System	Pearl Harbor System
Cumulated Rainfall in Normal Monthly Units equivalent to One Foot of Head	1.115	1.486
Draft equivalent to One Foot of Head (Scale Units)	5.78	8.20
Draft equivalent to One Foot of Head (M.G.D.)	5.78	41.0

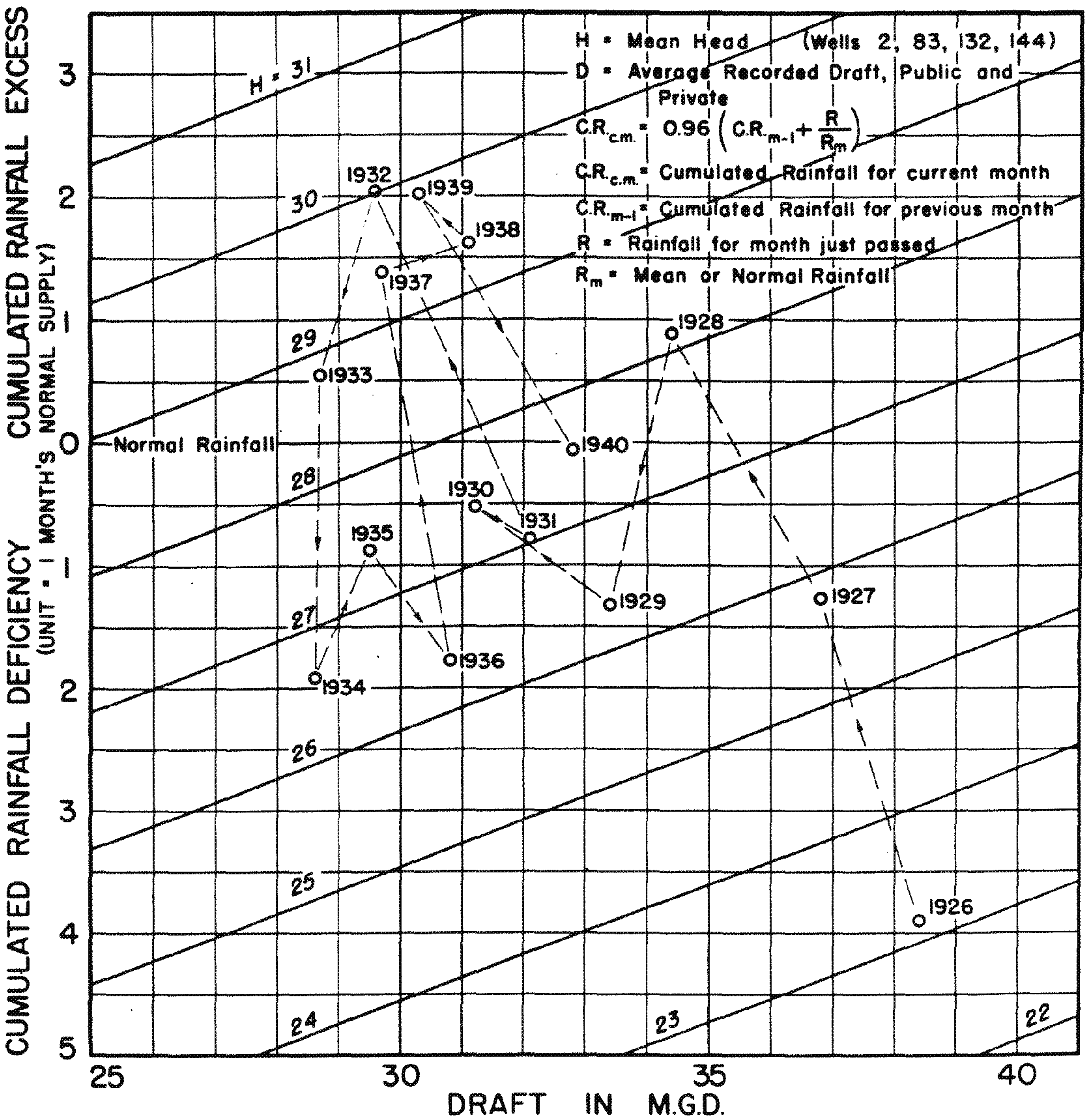
Since the heads in the two areas are of similar order and the other scales are relative rather than absolute, one would expect to find the relationship of rainfall to head the same in similar systems, and the scale relationship of draft to head to be the same and the absolute quantities in the ratio 1 to 5. This is not the case, and there appear to be some real differences other than size between the two systems. The difference is described by stating that head in the Pearl Harbor system is less responsive to rainfall changes in the ratio 0.75 and to comparable draft changes in the ratio 0.705 than is head in the Honolulu system. This is consistent with the observation that has been made elsewhere that the equilibrium of the Pearl Harbor system seems more like that of a stream, rather than of a lake.



PEARL HARBOR ARTESIAN SYSTEM AREA "6"

$H = 25.75 + 0.673\ C.R._{c.m.} - 0.0244\ D$

Figure 2 - Graph showing multiple correlation between Head, Draft, and Cumulated Rainfall, in the Pearl Harbor area. These studies are continuing and some improved correlations have been derived since this illustration was arranged.



HONOLULU ARTESIAN SYSTEM AREAS 1, 2, 3, 4.

$H = 33.30 + 0.897\ C.R._{c.m.} - 0.173\ D$

Figure 1 - Graph showing multiple correlation between Head, Draft and Cumulated Rainfall, in the combined Honolulu areas 1, 2, 3, and 4. This correlation with a particular function of rainfall is one of various types. Since arranging this graph better types have been worked out and more accurate correlations achieved. Inquiry should be made of the division of geology before quoting or using the data offered here.

The fact that the slopes of the head lines in the two graphs are nearly identical or, what is equivalent, that the two ratios just given are nearly identical, indicates that the ratio between rainfall and draft is practically the same in the two systems. This is of course based on the assumption of a 5 to 1 ratio between the two. On the other hand, if we use the graph to determine the absolute amount of draft equivalent to a maintained one-month excess of cumulative rainfall in the two systems, we get 5.184 M.G.D. for the Honolulu area and 27.59 M.G.D. for the Pearl Harbor system, which gives a ratio of draft capacity between the two areas under comparable rainfall conditions of 5.32.

In the following table is given the presumptive value of a year of rainfall 50% in excess of normal for the two basins. It should be understood that these are based on the assumptions stated above and refer to existing operating conditions. We have no valid basis for calculating the effects of changes, such as transfer of draft wholly from wells to basal shafts, though if such change were accompanied by sealing of wells, there can be little doubt that it would be beneficial.

APPROXIMATE PRESUMPTIVE BENEFITS IN QUANTITIES OF WATER (2)

	Honolulu System	Pearl Harbor System
A year of rainfall, uniformly 50% in excess of normal. Then return to normal. (This is approximately the maximum deviation of the past fifteen years)		
During the year, average (M.G.D.)	14.0	74.5
At the end of the year (M.G.D.)	24.1	128.3
One year later (1) (M.G.D.)	14.8	78.6
Five years later (1) (M.G.D.)	2.0	10.6

(1) The reader will understand that in actual behavior these declining effects are always masked by the current excesses or deficiencies and are not apparent. On the other hand, it is helpful to realize that actual conditions at any given time do represent a summation of an infinite number of terms of approximately the character here postulated.

(2) There is nothing in the material set forth in this appendix which on its face either affirms or denies the condition of bottom storage which has been discussed elsewhere. Whether the effect of bottom storage is large, small, or zero, it is included in the simplified form of the equations derived.

The assumption of one year of rainfall 50% in excess of normal is found to build a cumulated excess of 4.65 months of rainfall, which is materially greater than the maximum excesses built by either the Honolulu rainfall (2.13 in June, 1939) or the Pearl Harbor rainfall (3.20 in May, 1938) between 1925 and 1940. It is about the same as the deficiencies reached during that period, (Honolulu, —4.39, November, 1926) (Pearl Harbor, —4.74, November, 1926). We have no direct evidence that on this scheme of computation, total cumulated excesses can exceed 3 months of rainfall, nor deficiences exceed 5 months of rainfall, but probability theory and calculations would furnish a guide as to what extremes might occur during longer periods.

There are various ways in which the equations, and the two graphs can be used to obtain figures which have an estimatable degree of validity. Given two of the three values, head, cumulated rainfall and draft, we can get a figure for the third. For example, under rainfall conditions and head stipulations as shown, the safe draft for the combined areas 1, 2, 3, and 4, is as follows:

TABLE OF SAFE DRAFTS

Cumulated Rainfall Condition	Mean Head held at 30 feet	Mean Head held at 27 feet	Mean Head held at 24 feet
2-Month Excess	29.5	(1)	(1)
1-Month Excess	24.3	41.6	(1)
Normal	(2)	36.4	(1)
1-Month Deficiency	(2)	31.2	(1)
2-Month Deficiency	(2)	26.0	43.4

(1) These estimated values are greater, but they come outside the range on which the equation is based and the data probably do not justify this degree of extrapolation.

(2) These values are smaller, but likewise cannot justificably be read from the graph.

There are many more refinements to be brought into these calculations but the central figure of 36.4 M.G.D. as the draft available at normal rainfall with the mean head held at 27 feet (1)

(1) This is equivalent to approximate heads as follows, Moiliili 26.6, Beretania 28.6, Kalihi 27.65, and Moanalua 25.15, and is about 0.56 feet lower than average for 1925-1940.

is probably valid to within about plus or minus 2.3 M.G.D.

Preliminary experiments in expanding these calculations to give separate results for the several areas of the Honolulu system and to eventually yield valid figures on storage capacity, lateral leakage, and the various other data sought in the mechanical testing program offer substantial encouragement that practical results of great value can be obtained. Essential difference in procedure from that earlier followed lies in (1) tentative use of the cumulated rainfall index, (2) transfer of emphasis from use of periods of supposed constant or fixed conditions to the use of longer term averages of recognized variable conditions, and (3) use of the statistical procedure for incorporation of larger volumes of data rather than of algebraic methods for solution of equations based on limited number of fixed measurements, (4) exploration of the problem by short steps rather than attempt at complex simultaneous equations.

Since the foregoing text was written, about ten other forms of the rainfall function have been ~~tired~~ tried, solving the equation in another form

$$\text{Draft} = x + y(R_c) + z(\text{Head})$$

In this series, the approximate minimum probable error of 1.16 M.G.D. has been established, and is approached by several of the Rainfall functions.

It appears that this residual error is due to another factor not yet introduced into the equation. Progressive details of this study will be presented later.

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